PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H01S 3/091	A1	(11) International Publication Number: WO 98/52257 (43) International Publication Date: 19 November 1998 (19.11.98)

(21) International Application Number: PCT/US98/09594

(22) International Filing Date: 12 May 1998 (12.05.98)

(30) Priority Data:

08/854,814	12 May 1997 (12.05.97)	US
08/854,813	12 May 1997 (12.05.97)	US

(63) Related by Continuation (CON) or Continuation-in-Part (CIP) to Earlier Applications

US	08/854,814 (CIP)
Filed on	12 May 1997 (12.05.97)
US	08/854,813 (CIP)
Filed on	12 May 1997 (12.05.97)

(71)(72) Applicant and Inventor: DAHM, Jonathan, S. [US/US]; 582 Oregon Avenue, Palo Alto, CA 94301 (US).

(74) Agent: ABRAHAM, David, J.; Wilson Sonsini Goodrich & Rosati, 650 Page Mill Road, Palo Alto, CA 94304-1050 (US).

(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, GM, GW, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

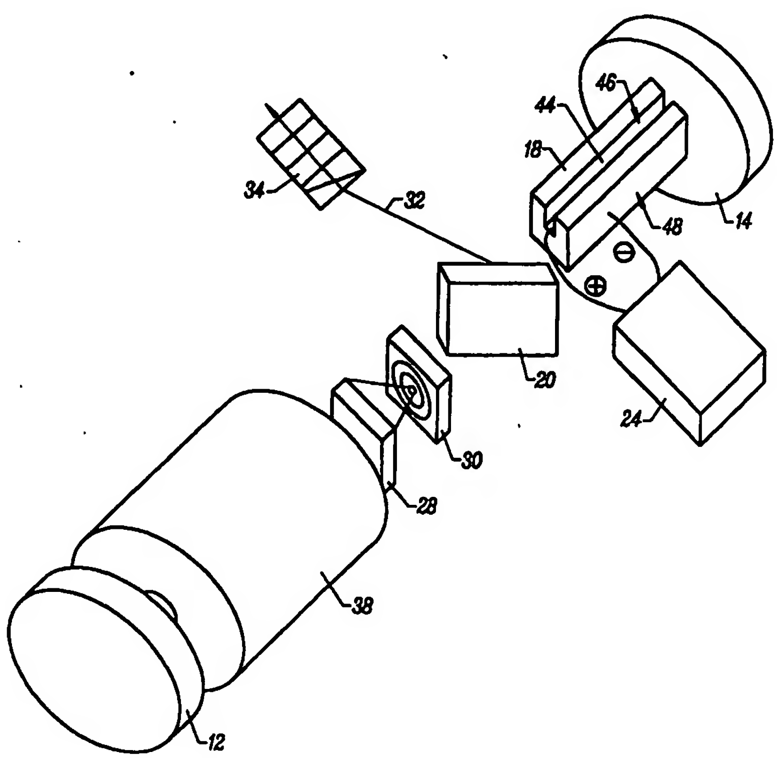
Published

With international search report.

(54) Title: IMPROVED LASER CUTTING APPARATUS

(57) Abstract

Disclosed are lasers and laser systems including a resonator cavity (10) including an optical path; a gain medium (16) positioned in the resonator cavity (10) along the optical path; an electro-optic device (18) positioned in the resonator along the optical path; a polarizer (20) positioned in the resonator cavity along the optical path; a pump source (22) generating a pump beam incident on the gain medium (16) to produce an intercavity beam that is incident on the surface of the polarizer to produce a polarized output beam, wherein the polarized output beam has an average power of at least 40 W; and a high voltage pulser (24) coupled to the electro-optic device (18) and generating a voltage pulse to the electro-optic device (18), wherein the polarized output beam has a pulsewidth which does not exceed 1.5 nanoseconds with a pulse repetition frequency of at least 100 kHz.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece	ML	Mali	TR	Turkey
BG	Bulgaria	HU	Hungary	MN	Mongolia	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MR	Mauritania	UA	Ukraine
BR	Brazil	IL	Israel	MW	Malawi	UG	Uganda
BY	Belarus	IS	Iceland	MX	Mexico	US	United States of America
CA	Canada	IT	Italy	NE	Niger	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NL	Netherlands	VN	Viet Nam
CG	Congo	KE	Kenya	NO	Norway	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NZ	New Zealand	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	PL	Poland		
CM	Cameroon	KR	Republic of Korea	PT	Portugal		
CN	China	KZ	Kazakstan	RO	Romania		
CU	Cuba	LC	Saint Lucia	RU	Russian Federation		
CZ	Czech Republic	LI	Liechtenstein	SD	Sudan		
DE	Germany	LK	Sri Lanka	SE	Sweden		
DK	Denmark	LR	Liberia	SG	Singapore		
EE	Estonia						

IMPROVED LASER CUTTING APPARATUS

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to methods and apparatus for high precision cutting, and more particularly, a diode pumped laser with short pulsewidth and high pulse repetition frequency for silicon wafer dicing.

Description of Related Art

Cutting operations are extremely important material handling operations. From trimming sheet metal to precisely cutting silicon wafers, cutting operations are central to the efficient processing of materials. Typical cutting methods and apparatus involve mechanical cutters: saws and the like. Often, mechanical cutting methods and apparatus are disadvantageous in precision cutting operations because they generate debris, and may unduly stress the material being cut.

Lasers are a natural alternative to mechanical cutting, in applications where mechanical cutting is inadequate. Unfortunately, conventional laser designs suffer from a number of deficiencies when applied to cutting operations. They can have very high energy operating costs, especially when compared to mechanical cutting. Additionally, they create unacceptable cutting defects, such as spattering or thermal defects. As a result, the use of industrial lasers for cutting has been limited to applications where the defects, energy cost and other drawbacks are acceptable, and where mechanical cutting is not an acceptable option.

A particular example of a cutting operation where laser cutting would be a desirable way of cutting is dicing. Dicing is a cutting operation used to separate integrated circuits (ICs) from their parent wafers. The dicing of IC patterned silicon wafers currently relies on a technology initially developed in the early 1970's. The dicing step is performed mechanically by a two-and-one-half inch diameter diamond-impregnated circular saw blade running at extremely high rpms, lubricated by large

amounts of water. Material removal occurs through the creation of micro-cracks at the point of contact between the diamond particles and the substrate. As micro-cracks intersect, debris is generated and cutting takes place.

This mechanical dicing method introduces variables that are disadvantageous to the cutting process. The use of diamond embedded blades requires the use of water for lubrication, cooling, and washing away silicon particles. Water in contact with the processed wafer surface creates substantial contamination problems for the ICs and waste water disposal issues, as well as reduces throughput due to the time necessary to dry the wafers. The problem of blade wear requires frequent dressing and changing of the blades, resulting in down time of equipment, and the increased possibility for reproducibility problems.

Current dicing equipment is restricted to uni-directional cutting because the cutting head must be fixed, with movement provided by the substrate positioning stage. The circular blade also restricts the flexibility of cutting geometry to straight lines and 90 degree corners. In addition, the width of the blade restricts the kerf, or cut width, to approximately 25-37.5 microns. The ability of future dicing blade technology to reduce this kerf, and thus increase IC population per wafer, is limited.

The depth of damage and the size of the kerf depend on many different variables, some relating to the properties of the silicon and others to the capabilities of the circular cutting device. A short list of the variables includes the chemical properties of the silicon, blade parameters such as vibration, relative motion of the blade and workpiece, up or down cutting, and the chemistry and delivery of lubricants. The level of damage to the silicon wafer is characterized by the length and distribution of micro-cracks, and the penetration of dislocations. Most importantly, the length and distribution of micro-cracks can influence the future reliability of the IC.

Currently, dicing saw technology allows for a maximum speed of travel across the silicon wafer of approximately 50-75 mm/s. The processing speed of silicon wafers is of extreme importance because it directly translates to higher throughput of the processed substrate. Unfortunately, cut quality is difficult to maintain at high processing speeds due to increased chipping of the substrate and reproducibility problems relating to increased blade wear. In general, attempts to increase the

throughput of the process by increasing the cutting speed have resulted in either inferior cut quality, unacceptable blade wear, or both.

The requirement for high cut quality and speed demands the inclusion of many expensive internal components in the current generation of dicing equipment. A large expense relates to the need for very low vibration of the 60,000 rpm blade. Due to the brittle nature of the silicon substrate, the slightest vibration can induce fractures. To minimize vibrational perturbations, the blades are mounted on ultra-expensive air-bearing spindles. Also, the electric inverter needed to operate a motor at high and precise rpms is expensive.

Since the infancy of dicing technology, various academic and industrial labs have attempted to use laser devices to dice silicon wafers. Unfortunately, the results have been less than favorable. In the 1970s, laser dicing of silicon wafers was tried unsuccessfully. The primary shortcomings were cut quality (surface smoothness) and re-solidified material on the wafer surface. The main culprit was the pulsewidth of the irradiated energy: a microsecond-long pulse was far too long a period to prevent destructive heat dissipation into a significant portion of the area immediately surrounding the cut. The difficulty with these longer pulsewidths (actually 1 nanosecond and longer) is that the pulse interacts with the material for too long a time, and the heat affected zone penetrates deep into the substrate.

Recently, one of the largest U.S. manufacturers of dicing saws analyzed the comparative results of conventional blade dicing and laser dicing. The study found that the depth of damage was greater for the laser diced wafers resulting in a lower fracture strength of the silicon substrate. The report stated that the increased damage created by the laser was a result of thermally induced stresses.

These stresses result from excessive heat deposition into the wafer causing collateral damage to the areas of the wafer proximal to the cut. This collateral damage is characterized by micro-cracking and spatter, both entirely unacceptable attributes. The individual silicon chips, or die, that are produced by the dicing of the wafer cannot have micro-cracks exceeding 1 micron in length. Longer cracks are potential future failure sites, as these cracks might eventually propagate due to thermal cycling or vibrations encountered in the field.

Cutting lasers can operate in a wide variety of wavelengths, depending upon the particular application. For example, near infra-red (NIR) lasers may be used for high speed applications due to their ability to generate greater power than their ultra-violet (UV) counterparts. Unfortunately, in the case of dicing, NIR wavelengths propagate deep into silicon substrates before being absorbed because silicon is semi-transparent at these wavelengths. This results in excess energy deposition deep into the substrate. UV dicing lasers have been used in the past to alleviate this problem, because silicon is highly absorptive to UV wavelengths. However, UV lasers can not develop sufficient power to process silicon at high speeds.

Recently, researchers have found that the deep absorption depth problem associated with near-IR lasers in silicon can be reduced using ultra-short pulse widths. Ultra-short pulse widths may promote the formation of a near solid density plasma, which acts as a highly energy absorptive layer. The absorbing properties of the plasma may reduce the transmission of excess energy deep into the substrate.

Ultra-short pulses alone will not make a feasible laser silicon dicing system. While known ultra-short pulse techniques may reduce the deep absorbtion depth problems, the cutting speeds with such techniques are still too slow for high speed cutting applications, especially dicing operations.

It is highly desirable in the semiconductor manufacturing industry to increase the speed of dicing operations, as this results in a significant cost benefit due to higher throughput. However, it is imperative that the quality of the cuts not be compromised by an increase in speed. Known dicing methods, whether mechanical or laser, have not allowed an increase in cutting speed without an unacceptable loss in cut quality. Additionally, as noted above, known laser cutting methods suffer from a number of defects and problems that limit the expansion of their use in a wide variety of industrial and other cutting operations.

There is therefore a need for methods and apparatus for improved laser cutting of various materials. In particular, there is a need for methods and apparatus involving lasers suitable for silicon wafer dicing with high cutting speeds.

SUMMARY OF THE INVENTION

In an aspect, the invention relates to lasers comprising a resonator cavity including an optical path; a gain medium positioned in the resonator cavity along the optical path; an electro-optic device positioned in the resonator along the optical path; a polarizer positioned in the resonator cavity along the optical path; a pump source generating a pump beam incident on the gain medium to produce an intracavity beam that is incident on a surface of the polarizer to produce a polarized output beam, wherein the polarized output beam has an average power of at least 40 W; and a high voltage pulser coupled to the electro-optic device and generating a voltage pulse to the electro-optic device, wherein the polarized output beam has a pulsewidth which does not exceed 1.5 nanoseconds with a pulse repetition frequency of at least 100 kHz.

In another aspect, the invention relates to lasers systems comprising a resonator cavity including an optical path; a gain medium positioned in the resonator cavity along the optical path; an electro-optic device positioned in the resonator along the optical path; a polarizer positioned in the resonator cavity along the optical path; a pump source generating a pump beam incident on the gain medium to produce an intracavity beam that is incident on a surface of the polarizer to produce a polarized output beam; an amplifier coupled to the resonator cavity and amplifying the polarized output beam to provide an amplified polarized output beam of 40 W or greater; and a high voltage pulser coupled to the electro-optic device and generating a voltage pulse to the electro-optic device, wherein the amplified polarized output beam has a pulsewidth which does not exceed 1.5 nanoseconds with a pulse repetition frequency of at least 100 kHz.

In yet another aspect, the invention relates to lasers systems for removing material from a substrate comprising a resonator cavity including an optical path; a gain medium positioned in the resonator cavity along the optical path; an electro-optic device positioned in the resonator along the optical path; a polarizer positioned in the resonator cavity along the optical path; a pump source generating a pump beam incident on the gain medium to produce an intracavity beam that is incident on a surface of the polarizer to produce a polarized output beam, wherein the polarized output beam has an average power of at least 40 W; a high voltage pulser coupled to the electro-optic device and generating a voltage pulse to the electro-optic device, wherein the polarized output beam has a pulsewidth which does not exceed 1.5 nanoseconds at a pulse repetition

frequency of at least 100 kHz; and a substrate holder for holding and positioning the substrate in a path of the polarized output beam.

In still another aspect, the invention relates to lasers comprising a resonator cavity including an optical path; a gain medium positioned in the resonator cavity along the optical path; an all-optical switching mirror positioned at an end of the resonator cavity; a laser diode pump source generating a pump beam incident on the gain medium to produce an intracavity beam that is incident on a surface of the all-optical switching mirror to produce an output beam.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 shows a schematic representation of a cutting surface that might be generated during practice of the invention.

FIG. 2 is a graph showing various wave forms of laser pulses.

FIG. 3 is a graph illustrating the difference in duration between two laser pulses having similar rise times.

FIG. 4 shows three spacial distributions of pulses that can be used in the methods and apparatus according to the invention.

FIG. 5 is a cross sectional view of an embodiment of a laser according to the invention.

FIG. 6 is a cross-sectional view of another embodiment of the laser, taken through a central portion thereof.

FIG. 7 is a perspective view of yet another embodiment of the laser.

FIG. 8 is a side view of yet another embodiment of the laser.

FIG. 9 is a side view of yet another embodiment of the laser.

FIG. 10 is a side view of yet another embodiment of the laser.

FIG. 11 is a side view of yet another embodiment of the laser.

FIG. 12 is a side view of yet another embodiment of the laser.

FIG. 13 is a side view of yet another embodiment of the laser.

FIG. 14 is a side view of yet another embodiment of the laser.

FIG. 15 is a side view of yet another embodiment of the laser.

FIG. 16 is a side view of yet another embodiment of the laser.

FIG. 17 is a side view of yet another embodiment of the laser.

FIG. 18 is a side view of yet another embodiment of the laser.

FIG. 19 is a side view of yet another embodiment of the laser.

FIG. 20 shows a cross-sectional view of an embodiment of an all-optical thin film switching mirror according to the invention.

FIG. 21 shows a cross-sectional view of another embodiment of an all-optical thin film switching mirror according to the invention.

FIG. 22 shows a cross-sectional view of yet another embodiment of an all-optical thin film switching mirror according to the invention.

FIG. 23 shows a side elevation of a cross section of a laser according to the invention.

FIG. 24 shows a cross section of a micro-chip laser according to the invention.

FIG. 25 shows a cross section of a thin disk laser according to the invention.

FIG. 26 shows a cross section of a fiber laser according to the invention.

FIG. 27 shows a cross section of a monolithic laser according to the invention.

FIG. 28 shows a cross-section of a laser, according to the invention, with specific emphasis on flex circuit assembly providing power to a diode array.

FIG. 29 shows a cross-section of a rod and flow tube end block assembly, i.e. an integrated binder bolt system, according to the invention.

FIG. 30 is a cross-sectional view of another emodiment of a laser according to the invention.

FIG. 31 is a side view of one embodiment of a corrector plate.

FIG. 32 is a side view of another embodiment of a corrector plate.

FIG. 33 is a schematic of a laser system according to the invention.

FIG. 34 is a side cross-sectional view of a laser system according to the invention showing a vacuum pick-up.

DETAILED DESCRIPTION

FIG. 1 shows a schematic representation of a cutting surface that might be generated during practice of the invention. Cutting surface 101 includes lens 103, laser beam 105, substrate 107, shockwave 109, heatwave 111, melt region 113, vapor region 115, plasma region 117, and ejected molten material 121.

In operation, laser beam 105 is focused through lens 103 to illuminate substrate 107. Various substrates may be cut using the inventive methods and apparatus. In a preferable embodiment, the substrate comprises semiconductors, dielectrics, polymers, metal, natural materials, and mixtures thereof. In a more preferable embodiment, the semiconductors comprise silicon, gallium arsenide, or diamond. In a most preferable embodiment, the substrate is a silicon wafer. The action of the laser beam heats and ionizes the substrate creating a plasma region 117, near the cutting surface. The plasma region absorbs the beam and creates emanating heatwave 111. The heatwave acts on the substrate to create vapor region 115. Over time, the heatwave forms melt region 113. The energy of the laser beam creates expanding vapor which acts to create emanating shockwave 109. The shockwave acts to eject molten material 121 from the melt region, thus removing the material from the substrate. The cutting surface is then propagated, as shown by direction arrow 122, through the substrate to produce a cutting action.

An useful effect of the inventive method and apparatus occurs when substantially all of the pulses have both a rise time to pulse length ratio sufficiently small enough and a fluence sufficently large enough to enable the heatwave to travel sufficiently faster than the shockwave to promote removal of the vaporized substrate material from the cutting surface. This action results in a cutting effect that is faster than a cutting effect that only consists of removal of vaporized material without the shockwave expulsion of molten material.

Additionally, in for certain substrates, such as semiconductors, greater absorbtion of the impinging laser beam can be obtained if the beam is substantially P-polarized at grazing incidence to the cutting surface (also known as the cutting front along which the cut progresses). In metals, the reverse is true. The polarization may be rotated in the direction of the cut or perpendicular to the cut using a electro-optic crystal with an applied voltage or a wave plate with a motorized rotational stage. In a preferable embodiment, the stream of light pulses is substantially P-polarized.

This emission of pulses is repeated at a particular pulse repetition frequency (PRF). In a preferrable embodiment, the light pulse frequency according to the invention ranges from about one hundred kilohertz to about five megahertz. In a more preferrable embodiment, the light pulse frequency according to the invention ranges

from about one megahertz to about five megahertz. In a most preferrable embodiment, the light pulse frequency according to the invention ranges from about one megahertz to about 1.5 megahertz. In another preferrable embodiment, it is possible to optimize the PRF for the particular cutting task and substrate, etc.

The inventive method and apparatus permits the generation light pulses with good beam quality. In a preferable embodiment, the light pulses according to the invention have an M-squared value less than about five. In a more preferable embodiment, the light pulses according to the invention have an M-squared value ranging from about one to about five. In a still more preferable embodiment, the light pulses according to the invention have an M-squared value ranging from about 1.25 to about two. In a preferable embodiment, the light pulses according to the invention are substantially multimode. In another preferable embodiment, the light pulses according to the invention are substantially only single mode.

In a preferable embodiment, the light pulses according to the invention are polarized either substantially randomly or substantially linearly. In a more preferable embodiment, the light pulses according to the invention are polarized substantially linearly.

The inventive method and apparatus permit the generation of streams of light pulses having high average power. In a preferable embodiment, the stream of pulses according to the invention has an average power of more than about ten watts. In a more preferable embodiment, the stream of pulses according to the invention has an average power of more than about twenty watts. In another more preferable embodiment, the stream of pulses according to the invention has an average power of more than about thirty watts. In a most preferable embodiment, the stream of pulses according to the invention has an average power of more than about fourty watts.

The inventive method and apparatus also permit generation of a wide range of wavelengths of light that may be optmized for the particular cutting operations at hand, and may depend on the substrate material, type of cutting operation, etc. In a preferable embodiment, the light pulses according to the invention have a wavelength ranging from about five hundred nanometers to about sixteen hundred nanometers. In a more preferable embodiment, the light pulses according to the invention have a wavelength ranging from about nine hundred and fifty nanometers to about eleven hundred

nanometers. In a most preferable embodiment, the light pulses according to the invention have a wavelength of about 1079.5 nanometers.

An alternative cutting method achievable using the invention is known as laser separation. Laser separation is a cutting method that differs from the above method of cutting in that it does not rely on removal of substrate material to acheive a cut, as does the previously discussed cutting method. Laser separation is typically used on glass and other brittle materials, as discussed generally in Kondratenko (U.S. Patent No. 5,609,284). Although understanding of the exact mechanism of laser separation is not necessary to practice this invention, and the inventor does not wish to be bound by any particular explanation, a general discussion of the hypothetical chemical basis for laser separation may be helpful for basic understanding. As currently understood, in laser separation, a laser beam is produced with sufficient power to slightly ionize the substrate along a desired path. The beam is directed along a desired path on the substrate, and the ionization of the substrate along the path presumably results in weakening of substrate molecular bonds along the path. It is next hypothesized that the substrate will then crack along that weakened path created by the laser beam. The thermal shock related to the fast rise time of the laser light pulses according to the invention would also contribute to crack formation and propagation.

Prior art attempts at inducing laser separation have focused on using a laser beam and adding further thermal stress to a local substrate area using a coolant (e.g. the method disclosed in Kondratenko). However, the inventive laser and cutting methods may obviate the need for a coolant boosting of thermal stress along the desired path.

Prior art lasers that have been presumably tried in laser separation tend to be either continuous wave or long pulse duration/low pulse repetition frequency lasers. These types of lasers presumably cause thermal stresses over relatively long portions of the substrate. Additionally, these types of lasers may create high thermal stresses, especially in concert with applied coolants, that result in uncontrolled substrate cracks. In contrast, the inventive ultra high pulse repetition frequency/the short pulse laser can be configured to produce smaller cracks, which may reduce the uncontrolled stress cracks of the prior art. This is because it might be easier to control a crack, short pulse by short pulse, rather than controlling a continuously produced crack.

If it prooves necessary to enhance thermal stress in a thin substrate, it is possible to accomplish this without the use of externally applied coolant. This is advantageous, because eliminating the coolant step removes a significant source of process variability and contamination. The inventive method encompasses the placement of an absorbing layer on the underside, upperside or in an internal portion of the substrate along the desired path for laser separation. This absorbing layer absorbs radiation induced by the laser beam preferentially with respect to the substrate, and generates thermal stress due to differential heating between the absorbing layer and the substrate material.

Suitable absorbing layers may be generated using laser marking, perhaps, in an oxidizing atmosphere, or could be generated using black india ink, inkjets, stencils, or pad printing methods. Other methods of creating the absorbing layer will no doubt occur to one of skill in the art, and are within the scope of the invention.

In a preferred embodiment, the laser used for laser separation has a wavelength that is transmitted through the substrate instead of absorbed. For example, if a Nd:$YAlO_3$ laser with a polarized output is used, the output wavelength is 1079.5 nm, when the gain medium is cut parallel to the B axis. This wavelength, however, is absorbed by a substrate, such as silicon, and therefore cannot be transmitted through the body of the sustrate to the absorbing layer. An alternative embodiment is to pump a gain medium, such as Nd:$YAlO_3$, that is cut parallel to the A or C axis. Another alternative embodiment may use high reflectors at a wavelength of approximately 1300 nanometers. This will result in a operating wavelength that is approximately 1320 to 1340 nanometers. Silicon is highly transparent in this region of the electromagnetic spectrum. Similar techniques might be used in other substrates, and other gain mediums, as is necessary to obtain the desired results. For example, Yb:$YAlO_3$ offers similar possiblities, as does Nd:YAG or Yb:YAG.

In another preferable embodiment, the inventive method and apparatus encompass illuminating the substrate with a stream of light pulses having a pulse repetition frequency ranging from about five hundred kilohertz to about five megahertz, a rise time of less than about five hundred picoseconds, and a duration ranging from about fifty picoseconds to about five hundred nanoseconds. In a more preferable embodiment, the pulses according to the invention have a maximum fluence ranging from about one hundred nanojoules to about one hundred millijoules.

FIG. 2 shows various wave forms of laser pulses. Wave form 202 is a square wave. Wave form 204 is a gaussian wave. Each of wave forms 202 and 204 have approximately the same fluence, or total energy. However, as can be seen from the graph, the square wave has higher intensity over its duration than the gaussian wave. This tends to promote ionization of a substrate that is being cut, and the creation of the vapor and plasma regions which provide benefits, such as shortening the thermal penetration of the pulse. Additionally, the rise time of the gaussian pulse is not as fast as the rise time for the square wave pulse. This difference in rise times contributes to a more efficient creation of the vapor and plasma regions in the cutting surface. This effect tends to promote a cleaner and faster cut per pulse. Square wave pulses are generally discussed in Liu Huang et al., Square Wave Pulsewidth Variable Solid State Laser, SPIE **2889**:196-202 (1996). Preferrable rise times for pulses according to the invention are less than about five hundred picoseconds. More preferrable rise times for pulses according to the invention are less than about three hundred picoseconds. Still more preferrable rise times for pulses according to the invention are less than about one hundred picoseconds. Most preferrable rise times for pulses according to the invention are less than about ten picoseconds.

FIG. 3 illustrates the difference in duration between 2 laser pulses having similar rise times. FIG. 3A shows a laser pulse having a total duration of 50 nanoseconds. FIG. 3B shows a laser pulse having a total duration of 500 nanoseconds. Although each pulse has similar rise times, the total fluence between the two pulses is significantly different. Accordingly, the pulse illustrated in FIG. 3B is at least equally efficient at creating the vapor and plasma regions, shown in FIG. 1, but provides enough fluence to melt a portion of the substrate in front of the shockwave caused by the expanding vapor. This is a more efficient cutting process than a cutting process that only relies on expulsion of vaporized material, such as approximately ten picosecond and shorter material processing, such as femtosecond material processing. In a preferrable embodiment, the light pulses according to the invention have a maximum fluence ranging from about one nanojoule to about one joule. In a more preferrable embodiment, the light pulses according to the invention have a maximum fluence ranging from about In a preferrable embodiment, the light pulses according to the invention have a maximum fluence ranging from about one hundred nanojoules to

about one hundred millijoules. In another preferrable embodiment, the light pulses according to the invention have a duration ranging from about five picoseconds to about ten nanoseconds. In a more preferrable embodiment, the light pulses according to the invention have a duration ranging from about fifty picoseconds to about five hundred nanoseconds.

FIG. 4 shows three spacial distributions of pulses that can be used in the methods and apparatus according to the invention.FIG. 4A is a representation of a top-hat spatial distribution pulse. FIG. 4B is an illustration of a gaussian spatially distributed pulse. FIG. 4C is an illustration of a "doughnut" spatially distributed pulse. Each pulse is shown in terms of a normalized distance from the pulse center in arbitrary units.

Any of these three spacial distribution of pulses may be used in practicing the invention. However, the top-hat pulse is preferred for cutting silicon, and many other cutting applications, because it provides a smoother cutting surface over a defined portion of the substrate. This is true because a significant portion of the energy in a gaussian pulse is delivered at an intensity that is not the maximum intensity. In contrast, substantially all of the energy delivered in a top hat spatial distributed pulse is delivered at or substantially at the maximum intensity. Additionally, a top hat pulse is desired when using all-optical switching mirrors, which are discussed in more detail below. This is because when a gaussian pulse is used, for example, the all-optical switching mirror will only switch the central, high intensity, portion of the pulse out of the cavity.

In a preferrable embodiment, the light pulses according to the invention have a spatial distribution comprising top hat, Gaussian, or doughnut spatial distributions. In a more preferrable embodiment, the light pulses according to the invention have a top hat spatial distribution. In a preferrable embodiment, the light pulses according to the invention have a temporal distribution comprising square wave, and triangle wave temporal distributions. In a more preferrable embodiment, the light pulses according to the invention have a square wave temporal distribution.

FIG. 5 shows a side view of one embodiment of the laser. A resonator cavity 10 has a length designed to generate the desired pulsewidth. The selection of resonator cavity length and other principles of laser design can be found in "Lasers," Anthony E.

Siegman, University Science Books, 1986. This document, and all documents cited to herein, are incorporated into this disclosure by reference, as if reproduced fully herein.

The resonator cavity 10 may contain two fully reflective mirrors 12 and 14 and a gain medium 16. In electro-optic cavity dumping, the gain medium 16 is a robust, naturally birefringent crystal such as $Nd:YVO_4$, $Nd:YAlO_3$, Nd:YLF, $Yb:YVO_4$, $Yb:YAlO_3$, or Yb:YLF. Preferably, the gain medium 16 is an $Nd:YAlO_3$ crystal improved with no color centers, available from FEE Idar-Oberstein, Germany. Previous $Nd:YAlO_3$ material would darken under the influence of UV or strong pump light. This of course leads to higher crystal temperature and much more aberration. The color centers have been reduced or eliminated by Preciosa Crystal, Ltd., Turnov, using a non-standard crucible material during crystal growth. FEE Idar-Oberstein uses similar procedures. When the $Nd:YAlO_3$ is used, with the optical axis parallel to the B axis, the wavelength of emission is 1079.5 nm, which is a preferred wavelength for dicing silicon wafers. In a cavity-dumped laser that utilizes an all-optical switching mirror, such as is discussed below, a birefringent gain medium is not a necessary requirement.

Ytterbium, as a rare earth dopant, is sometimes advantageous over neodymium, because ytterbium produces a three level system, whereas neodymium produces a four level system. Pumping the gain medium to a high degree during operation of the laser causes the gain medium to get hot, generally in the center of the gain medium. In a four level system, such neodymium; a hot gain medium will result in substantial population of a lower energy level that robs the laser of efficiency. This is known as thermal quenching. However, in a three level system, such as ytterbium, this is not the case. A substantial improvement in efficiency can be obtained under conditions that "pump" the gain medium to a high degree. Cavity dumped lasers with a short pulsewidth and high power may require high pump power densities due to the need for short gain medium length. Therefore three levels systems may be a preferable embodiment.

A self doubling crystal available from CREOL (Center for Research in Electro-optics in Lasers, University of Central Florida), called YCOB, may be incorporated into the inventive lasers and laser systems. YCOB may permit the doubling of the output wavelength of a NIR laser, thus producing green output light. Green light output is good for cutting silicon because silicon is opaque to that wavelength. It is also good for cutting other materials, because the beam can be focused to a smaller spot, because half

the frequency means the half theoretical diffraction limited focused spot. It also means twice as long of a depth of field. Longer depth of field has many processing applications for precision cutting, and especially deeper cutting and drilling because the spot stays focused for a longer linear distance before it expands again.

The gain medium 16 has an anti-reflective coating, such as a sub-wavelength structure. The sub-wavelength structure is a surface relief structure etched directly into the bulk substrate (or barrel of gain medium). A good rule of thumb is that the height of the structures should be approximately 40% of the value of the operational wavelength to achieve minimum reflectance. These structures are much more durable than thin films and cheaper too. They are available from Holographic Lithography Systems, Bedford, Massachusetts, and Rochester Photonics, Rochester, New York.

The resonator cavity 10 also contains an electro-optic device 18 positioned along the optical path. The electro-optic device 18 is a material which exhibits minimal ringing at frequencies above 100 kHz, such rubitium titanium arsenate (RTA), available from Crystal Systems, Walwick, New Jersey, potassium titanyl phosphate (KTP), or beta-barium borate (BBO). Preferably, the electro-optic device 18 is an ultra-high aspect ratio BBO crystal, available from Casix, Fuzhou, China, or Quantum Technology, Lake Mary, Florida.

The resonator cavity 10 also contains a polarizer 20 positioned along the optical path. The polarizer 20 is preferably a high P transmission polarizer, available from VLOC, Tarpon Springs, Florida. The polarizer 20 allows the output beam 32 to be directed out of the resonator cavity 10, directed through focusing optics 34 and directed to the workpiece 36. The output beam 32 may be randomly polarized and then polarized with the polarizer 20.

The gain medium 16 is pumped by a pump source 22. The pump source 22 can be a diode source, a diode bar, or a vertically-emitting diode array. By incorporating arrays of vertically emitting diodes, higher pump power density can be achieved because more emitters can be utilized for a given area. Additionally, a binary lens can be incorporated by etching on the emitter, or on a transparent material over the emitter. This enables control over pump radiation. These vertically-emitting diode arrays are available from IBM, Schenectady, New York, and Lucent Technologies, Morristown, New Jersey. The pump source 22 should be powerful enough to produce a polarized

output beam of at least 40 W. Preferably, the pump source 22 is comprised of aluminum-free diodes available from SLIC, Binghamton, New York.

The pump source 22 may be radially configured to side pump the gain medium 16. The pump source 22 may be surrounded by reflectors 38 which direct the output of the pump source 22 towards the gain medium 16. The pump source 22 may also side pump the gain medium 16 through radially arranged optical fibers. The pump source 22 is powered by a controllable power supply and cooler system 40.

The electro-optic device 18 is charged by a high voltage pulser 24. The high voltage pulser 24 may be comprised of field effect transistors, avalanche diodes, or photo-conductive switches. The high voltage pulser 24 may also be comprised of light-activated silicon switches, available from ECR, Inc., San Diego, California, or drift step recovery diodes (DSRDs), drift step recovery transistors (DSRTs), and silicon avalanche shapers (SASs), available from Megapulse, Ltd., St. Petersburg, Russia.

An electron beam/diamond high voltage pulser (availble from Alameda Applied Sciences, Alameda CA), can be incorporated in the lasers and lasers systems according to the invention. These high voltage pulsers can be used to generate a high voltage pulse needed to switch an electro-optic crystal. This high voltage pulser uses an electron beam shined into diamond, for example natural or CVD diamond. The electron beam is rastered across the surface of the diamond that has an anode and cathode attached to opposite sides and an electrical potential between the two. In a rest state, the current cannot flow across the diamond. But when an electron beam passes through the diamond, and is rastered from terminal to terminal, the diamond is locally ionized, thereby supplying free electrons. The current then flows across following the electron beam path. Because the electron beam can be rastered across diamond very, very fast (less than fifty picoseconds, it is possible to obtain a very, very short rise time, on the order of 50-100 picoseconds.

Solid state pulse sharpeners may be used to sharpen the edge of pulse generated by high voltage pulse generators. Kentek, Inc. (Great Britain), and Picosecond Pulse Labs, Inc. (Boulder, Colorado), for example, supply solid state pulse sharpeners based on a semiconductor that sharpens the front of a pulse. The semiconductor is preferrably gallium arsenide. Another example of a solid state pulse sharpener, used to sharpen the leading edge of the pulse is a silicon avalanche shaper, SAS, available from Megapulse

in St. Petersburg, Russia. The SAS is a solid state pulse sharpener based on silicon instead of gallium arsenide. Yet another example of a high voltage pulse sharpener is a magnetic charge line pulse sharpener. The magnetic charge line pulse sharpener uses a ferrite loaded line to erode the leading edge of the pulse to obtain sharper, or faster rise time.

The resonator cavity 10 may also contain an aberration correcting device 26. The aberration correcting device 26 may be comprised of one or more aberration correcting surfaces. The aberration correcting surfaces may be made up of a focusing plate 28 and a collimating plate 30. The aberration correcting surfaces may be gray process surfaces, available from Wavefront Sciences, Albuquerque, New Mexico. The aberration correcting surfaces may also be binary surfaces, aspheric surfaces, or spherical surfaces on a graded-index material. By utilizing gradient glass as the substrate, aspheric equivalence can be achieved with a spherical surface. It is cheaper to manufacture spherical surfaces than aspherical. These materials are available from Light Path, Albuquerque, New Mexico.

The resonator cavity 10 may also contain a mode selecting surface or device, which contains a binary surface that can customize the amplitude and phase of a laser mode. The idea is to reduce the fundamental mode loss to near zero while increasing the second-order mode loss to near 50% or more.

The resonator cavity 10 may also be coupled to an amplifier. By incorporating one or more diode-pumped laser amplifier stages in series, a small signal may be amplified by 3 orders of magnitude or more. This is advantageously used because it is relatively easy to produce a low power signal with a short pulsewidth and excellent spatial quality at megahertz repetition rates. Some examples of signal generating devices are fiber lasers and diode lasers. The signals from these devices may be injected into one or more amplifier stages for amplification to then produce a pulse that has all the qualities of the signal pulse plus sufficient energy to process material efficiently.

The resonator design may be stable or unstable. In a stable resonator the light rays are confined between the surfaces of the resonator mirrors and do not walk out past the edges. The diameter of the TEM_{00} mode is usually limited to a few millimeters or less. This does not advantageously use a large amount of the available gain in a laser

rod which has a diameter of 4 mm. In an unstable resonator, the light beam is no longer confined between the mirrors. A light beam in an unconfining or unstable resonator diverges away from the axis. Thus, a large percentage of the active medium gain may be used as the beam expands away from the axis of the gain medium instead of just using the central core.

A big advantage of the current design is that it uses cavity dumping, hence, no output coupler is required. Usually in unstable resonators, a variable reflectivity mirror must be utilized. These are erroneous and finicky.

For Q-switch operation only two particular voltages leading to quarter-wave and half-wave retardation are of interest. In the first case, the incident linearly polarized light is circular polarized after passing the cell, and in the second case the output beam is linearly polarized, but the plane of polarization has been rotated 90°.

For a quarter wave voltage to produce a linear polarized beam, the light must pass through the crystal twice. In any case it is reflected off the mirror and travels back through. It can then be rejected or dumped by the polarizer. However, if a half-wave voltage is used initially then after a single pass the beam is linear polarized and may be immediately dumped. This can be good in that no energy is "trapped" in the cavity being only circularly polarized.

When the dumped pulse or beam exits the resonator cavity 10, an element or surface may be used to corrects the aberrations present to achieve a smaller focused spot. This is especially good extra-cavity because aberrations introduced by the polarizer and/or BBO can be easily compensated for. This device may be aspheric, binary, or gray process.

FIG. 6 shows a cross-sectional view of another embodiment of the laser. The pump source 22 pumps the gain medium 16. The gain medium 16 is surrounded by a reflector 38. The reflector 38 is in turn surrounded by a heat sink 42.

FIG. 7 shows a perspective view of another embodiment of the laser. The electro-optic device 18 contains a channel 44, which serves to minimize the distance between the electrodes 46 and 48 and reduce the voltage necessary to induce birefringence.

FIG. 8 shows a side view of another embodiment of the laser. Here, the aberration correcting device 26 is comprised of a binary surface 48 on the end of the

gain medium 16 and a separate binary surface 50 located between the gain medium 16 and the polarizer 20.

FIG. 9 shows a side view of another embodiment of the laser. Here, the aberration correcting device 26 is comprised of an aspheric surface 52 located on the end of the gain medium 16 and a separate aspheric surface 54 located between the gain medium 16 and the polarizer 20. The aspheric surface is available from CNC Systems, Rochester, New York.

FIG. 10 is a side view of another embodiment of the laser. Here, the aberration correcting device 26 is comprised of binary etched surfaces 56 and 58 on the gain medium 16 and the polarizer 20, respectively.

FIG. 11 is a side view of another embodiment of the laser. Here, the aberration correcting device 26 is comprised of aspheric surfaces 60 and 62 located on the gain medium 16 and the polarizer 20, respectively.

FIG. 12 is a side view of another embodiment of the laser. Here, the aberration correcting device 26 is comprised of corrector plates with binary etched surfaces 64 and 66 located between the gain medium 16 and the polarizer 20. The polarizer 20 may be an α-BBO polarizing beam splitting cube.

FIG. 13 is a side view of another embodiment of the laser. Here, aberration correcting device 26 is comprised of an aspheric surface 68 ground onto the end of the gain medium 16, and an aspheric surface 70 ground onto the polarizer 20. The polarizer 20 may be a thin film polarizing beam splitting cube. By utilizing two thin film hypotenuse coated prisms with an air space between them, it is easier to increase the P-transmission to over 99%. These thin film polarizing beam splitting cubes are available from VLOC, Tarpon Springs, Florida.

FIG. 14 is a side view of another embodiment of the laser. Here, the aberration correcting device 26 is comprised of binary surfaces 72 and 74 etched on the gain medium 16 and the polarizer 20, respectively. The polarizer 20 may be a thin film polarizing beam splitting cube.

FIG. 15 is a side view of another embodiment of the laser. Here, the aberration correcting device 26 is comprised of corrector surfaces 78 and 80 located on each end of a monolithic block 76.

FIG. 16 is a side view of another embodiment of the laser. Here, the polarizer 20 is positioned between the electro-optic device 18 and the mirror 14.

FIG. 17 is a side view of another embodiment of the laser. Here, the mirror 14 is at an angle from the perpendicular to the gain medium 16 and the electro-optic device 18 has been positioned between the gain medium 16 and the polarizer 20.

FIG. 18 is a side view of another embodiment of the laser. Here, the mirror 14 is at an angle from the perpendicular to the gain medium 16 and the electro-optic device 18 has been positioned between the mirror 12 and the gain medium 16.

FIG. 19 is a side view of another embodiment of the laser. Here, the mirror 14 is at an angle from the perpendicular to the gain medium 16. The electro-optic device 18 is at an angle to the gain medium 16 and positioned between the mirror 14 and the polarizer 20.

FIGS. 20-23 illustrate various embodiments of the all-optical switching thin film stack mirror according to the invention. The all-optical switching mirror is a thin film structure on one or more surfaces of a substrate that contains at least one layer of a non-linear material. This non-linear material is preferrably a photo-refractive semi-conductor, but could be a photo-refractive glass, polymer, crystal, or other material.

The all-optical switching mirror alternates between high reflectivity and low reflectivity states in response to incident optical energy. The ratio between the reflectivity during the high reflectivity state and the reflectivity during the low reflectivity state is defined as the contrast ratio. A preferable contrast ratio for the all-optical switching mirror according to the invention is at least ten to one (10:1). When the all-optical switching mirror is placed at the output end of a laser resonator, and a high reflector is placed at the other end, an optical pulse will build-up between the two reflectors. The all-optical switching mirror is a high reflector (approximately 99% reflectivity) until sufficient optical energy is incident upon it. At this point. a change occurs in the refractive index of the all-optical switching mirror's internal photo-refractive material. This in turn causes a change in its reflectivity from that of a high reflectivity state to a low reflectivity state. The pulse then exits, or is "dumped", from the cavity. Another pulse then builds up, and the process is repeated at a characteristic pulse repetition frequency (PRF). The pump radiation incident on the laser gain media may be either continuous wave (CW) or pulsed. An appropriate selection between the

two may be made on the basis of several factors, such as peak power or efficiency requirements.

The all-optical switching mirror may be advantageously employed in a cavity dumped laser scheme due to its minimal impact on optical path length, extremely fast turn-on (to a low reflectivity state), simplicity (passive elements), and efficiency. The all-optical switching mirror does not increase the optical path length of a resonator like an Electro-Optic (EO) scheme does. This is because the all-optical switching mirror does not utilize a electro-optic crystal that impacts the optical path length by its length × refractive index. The switching speed of the mirror is generally determined by the speed at which free-carriers are generated by the two photon absorption process. Since this process takes place on a time scale on the order of picoseconds, the switching speed is very fast. In an EO arrangement, the switching speed is limited to the rise-time of the high voltage pulse, which is typically hundreds of picoseconds or more. Additionally, the all-optical switching mirror is a "passive" system vs. the EO "active" system. The passive system is inherently less complex and also much less expensive.

Finally, the efficiency of a continuous wave pumped laser may be increased when the all-optical switching mirror is substantially optimized to switch to the low reflectivity state when the internal pulse has built up to substantially its maximum intensity. While the optimization process can be accomplished empirically, substantial time reductions in the optimization process can be acheived using simulation software, such as those discussed in M. Cada, <u>All-optical Reflectivity Tuning and Logic Gating in a GaAs/AlAs Periodic Layered Structure</u>, Appl. Phys. Lett. **60**:404-06 (1992); and B. Acklin, <u>Bistable Switching in a Nonlinear Bragg Reflector</u>, Appl. Phys. Lett. **63**:2177-79 (1993). Also relating to overall efficiency is the fact that it is difficult for photons to be trapped in the cavity with a polarization state not matching that required to be "reflected" by a polarizing mirror, and out of the cavity in an EO system.

After the mirror "turns on" or switches to the low reflectivity state, the intra-cavity pulse is transmitted through the structure and exits the cavity. Preferably, the structure of the all-optical switching mirror comprises substantially transparent thin film layers, on a substantially transparent substrate. The overall structure is preferrably designed to have a very low absorption coefficient in the linear state. This is because the laser may generate high power at high PRF in the linear state where cumulative

absorption may cause detrimental thermal effects or even device failure. Additionally, absorbtion is considered during the non-linear state. The structure is therefore designed to minimize a thickness and/or period of the non-linear layer(s) to minimize detrimental thermal effects including pulse lengthening, optical limiting, and other efficiency degrading mechanisms during the non-linear state.

Two effects determine the non linear refractive index change for bistable devices. One is the third order non-linearity where index change is dependent on the intensity of light (single photon absorption resulting in bound electronic refraction, also known as the Kerr effect). The other one is the 5th order non-linearity where the index change is dependent on the square of the intensity (two photon absorption resulting in free-carrier refraction). They both have the same sign (negative) and depending on the actual intensity, one or the other dominates. The two photon refraction effects dominate under high intensities. Both effects compete with the thermal refractive index changes which are positive. This reduces the desired switching performance. Low absorption is preferable in the case when high intensities and high repetition frequencies are desired. Refractive index changes on the order of a approximately one percent are preferrable.

The all-optical switching mirror is most preferably comprised of a distributed feedback (DFB) thin film structure on a transparent crystalline substrate. A DFB structure is a periodic multilayer system. The structure includes at least one non-linear material whose refractive index is dependent on the light intensity. The multilayer system further includes periods of layers alternating between high and low refractive index layers whose optical thickness is approximately equal to one-half the wavelength of incident coherent light. Generally, the higher index layers comprises the non-linear material. The intensity variation of the light field in the non-linear material causes a refractive index variation, and this refractive index variation induces, in turn, a light intensity variation through the optical interference effect. With this feedback mechanism, the reflected or transmitted intensity can exhibit differential gain or hysterisis in its response to the incident intensity.

The all-optical switching mirror may be comprised of a Fabry-Perot etalon. In this scheme, the non-linear layer is placed between two mirrors, and changes in the refractive index of the layer change the optical path length between the mirrors. A DFB structure that contains a non-linear material may be placed between two mirrors that

comprise a Fabry-Perot etalon. The light intensity oscillating between the mirrors, or through the entire structure, varies as a result of the optical interference effect. Combining a DFB structure within a Fabry-Perot structure can reduce the required intensity for switching between low and high reflectivity states because the optical field intensity in the DFB region will be further increased by the resonance of the Fabry-Perot Cavity.

In a preferrable embodiment, the non-linear layers comprise single crystal CdTe material in a DFB structure grown on sapphire, with alternating layers of single crystal sapphire thin films and the CdTe single crystal thin films. High quality single crystal films can be grown because sapphire is lattice matched to CdTe. These films may be produced by MBE or sputtering, generally on heated sapphire EPI polished substrates. It is advantageous to use single crystal films because scattering losses are reduced compared to amorphous or polycrystalline films and the single crystal non-linear layer has fewer defects and "traps" that reduce electron recombination time. A reduction in recombination time can cause the mirror structure to switch back to a high reflective state from a low reflective state before the entire pulse is dumped from the cavity. In another preferable embodiment, structures comprised of polycrystalline or amorphous films are used. In a more preferable embodiment, polycrystalline or amorphous films are used in all-optical switching mirrors in ultra-short resonators, such as those found in micro-chip lasers and thin disk lasers. These films usually are more simple to grow and can be produced by evaporation, sputtering, sol-gel, CVD, or MBE.

The type of non-linear material that is employed is based upon the criteria of absorption coefficient both in the linear and non-linear state, refractive index both in the linear and non-linear state, carrier recombination time, damage threshold, intrinsic absorbtion, and scattering losses. Semiconductors such as CdTe, CdS, CdSe, MnCdTe, ClCdTe, V:CdTe, ZnS, ZnSe, GaP, GaAs, and Si might be considered. These semiconductors have non-linear photorefractive properties and may be used as the high index layer.

Low index linear layers may be chosen as compatible to a super lattice such as the single crystal GaAs/AlAs or GaAs/GaAlAs system. At 1 micron these systems are generally too absorptive. For example, single crystal CdTe/single crystal Al_2O_3 on Sapphire EPI substrates might be used. This system may be produced using Dual

Magnetron Sputtering on hot substrates with layer to layer uniformity on the order of ½ Å using thin film crystal monitors.

If polycrystalline low index linear materials are used there are many possible material combinations. Such materials are generally known in the art, and include low index candidates such as MgF_2, SiO_2, etc. High index candidates are also generally known in the art, and include TiO_2, NiO_5, and HfO_2, etc.

Fabry-Perot Structures may be produced most simply by using a non-linear substrate with dielectric mirrors deposited on either side. A problem with this is that the non-linear layer is generally very thick, thereby creating excessive absorption and detrimental effects such as optical limiting, thermal blooming, and scattering. Also, precise thickness control is difficult to maintain thereby introducing problems relating to control of the optical resonance effect as it pertains to optical interference and generation or control of a standing wave. Therefore, Fabry-Perot all-optical switching mirrors are preferrably produced from a transparent linear substrate with thin film mirror stacks on both sides and at least one non-linear layer between the mirrors. The non-linear layer can be included in a DFB structure with or without a phase matching layer between the two mirrors.

Preferably, a sapphire EPI polished substrate on the order of 0.25-1 mm thick is employed with a high reflectivity dielectric stack on one side of the substrate. On the other side of the substrate, single crystal CdTe/single crystal Al_2O_3 can be grown in a DFB structure. A phase matching layer can be employed. A final high reflectivity stack of thin films comprising of dielectric linear layers may be employed to complete the Fabry-Perot cavity.

The Fabry-Perot cavity does not have to have a DFB structure between the mirrors. One layer of non-linear material is sufficient, but problems pertaining to efficiency, contrast ratio, and optical power required for switching would be encountered.

Photorefractive polymer substrates and/or thin films offer other possible combinations in addition to those outlined above for all-optical switching mirrors. Also, photo refractive glasses, when used as substrates and/or thin films offer additional possibilities.

FIG. 20 shows an embodiment of an all-optical thin film switching mirror according to the invention, in cross section. Shown are stack substrate 2002, and distributed feedback structure 2004. The distributed feedback structure includes linear layers of the distributed feedback structure 2006, and non linear layers of the distributed feedback structure 2008.

The linear layers 2006, and non linear layers 2008, are alternately coated and adhered to one another to form distributed feedback structure 2004. The distributed feedback structure is attached to a surface of stack substrate 2002.

FIG. 21 shows an all-optical switching mirror, according to the invention, shown in cross section. Included are linear dielectric thin film stack 2102, stack substrate 2104, non-linear layer or layers 2106, and linear dielectric thin film stack 2108.

On one surface of stack substrate 2104 is attached linear dielectric thin film stack 2102. On an opposing surface of the stack substrate is attached non linear layer or layers 2106. On the opposite side of the non linear layer or layers from the stack substitute is attached linear dielectric thin film stack 2108.

FIG. 22 shows an all-optical switching mirror, according to the invention, that is a combination of a Fabry-Perot structure and a distributed feedback structure, and is shown in cross section.

Shown are linear dielectric thin film stack 2202, stack substrate 2204, distributed feedback structure 2206, non-linear layers of the distributed feedback structure 2208, linear layers of the distributed feedback structure 2210, and linear dielectric thin film stack 2212.

Located on one surface of stack substrate 2204 is linear dielectric thin film stack 2202. Located on an opposing surface of the stack substrate is the distributed feedback structure. Included in the distributed feedback structure are non linear layers of the distributed feedback structure 2208, and linear layers of the distributed feedback structure 2210. These layers are laid down in an alternating fashion. Located on the surface of the distributed feedback structure farthest from the stacked substrate is linear dielectric thin film stack 2212.

In operation, the all-optical switching mirror may function as a combined Fabry-Perot/distributed feedback structure (DFB) all-optical switch, as has been discussed above.

FIG. 23 shows a side view of a cross-section of a laser, according to the invention. Included in laser 2300 are diffractive surface substrate 2302, diffractive surface 2304, laser rod 2306, laser diodes 2308, reflector 2310, thin film stack 2312, and thin film stack substrate 2314.

Laser rod 2306, possessing a distill and proximal end, is surrounded on its longitudinal length by laser diodes 2308. On a side of laser diodes 2308 opposite from the laser rod, are located reflectors 2310. At a proximal end of the laser rod is located diffractive surface substrate 2302. On a surface of the diffractive surface substrate facing towards the laser rod is located diffractive surface 2304. On the distal end of the laser rod is located thin film stack substrate 2314. On a surface of a thin film stack substrate facing the laser rod is located thin film stack 2312.

In operation, laser diodes 2308 serve to pump laser rod 2306. The laser diodes have sufficently low divergence, and are placed close enough to the gain medium, to not require a lens or lenses to have an efficient pump distribution overlap to a low order mode volume. Reflectors 2310 reflect any laser light emitted by the laser diodes away from the rod and direct such light towards the laser rod, thus enhancing the pumping effect of the laser diodes. Laser light from the laser rod strikes diffractive surface 2304. The diffractive surface contains etched optical elements that perform various optical functions, including, but not limited to, aberration correction, top-hat spacial wave form distribution generators, and higher order mode suppression. Located at the distal end of the laser rod is thin film stack 2312, which serves as an all-optical switch for selectively allowing laser light contained in the laser rod to pass through the thin film stack and a thin film stack substrate 2314. Such passage of laser light through the thin film stack and the thin film substack substrate is known as dumping the cavity. Thus, laser 2300 is known as a cavity dumped laser. Laser cavity dumping using bistable devices is generally discussed in J. Gea-Banacloche et al., Laser Cavity Dumping Using Optical Bistability, Optics Communications 46:43-46 (1983).

In a most preferable embodiment, the inventive methods and apparatus encompass providing a laser that produces a stream of light pulses, wherein the

frequency of pulses are about one megahertz; each pulse has a top hat spatial distribution; a square wave temporal distribution with a rise time of less than about ten picoseconds; a maximum fluence of about one millijoule; a duration of about six hundred and fifty picoseconds; the pulses having an M^2 of about one point five; a substantially linear polarization state, a wavelength of about one thousand seventy nine point five nanometers; and being substantially single mode; illuminating a surface of the substrate with the stream of light pulses, propagating a cutting surface created on the surface of the substrate by the stream of light pulses, with a heatwave and a shockwave emanating from the cutting surface and vaporized substrate material present near the cutting surface, and a near solid density plasma being formed near the cutting surface, and substantially all of the pulses having both a rise time to pulse length ratio sufficiently small enough and a fluence sufficently large enough to enable the heatwave to travel sufficiently faster than the shockwave to promote removal of the vaporized substrate material from the cutting surface.

FIG. 24 shows a cross-section of a micro-chip laser, having an all-optical switching mirror, according to the invention. Additional description of micro-chip lasers generally can be obtained from Coherent Laser, Inc. (Santa Clara, CA). Laser 2400 includes laser diode array 2402, focusing lens 2404, anti-reflective/high reflector coating 2406, gain medium 2408, and all-optical switching mirror thin film stack 2410.

On an emitting surface of laser diode array 2402 is located focusing lens 2404. On the other side of the focusing lens from the laser diode array is located anti-reflective high reflector coating 2406. On the side of the anti-reflective/high reflector coating opposite from the laser diode array and focusing lens is located gain medium 2408. On a side of the gain medium opposite from the anti-reflective/high reflector coating is located all-optical switching mirror thin film stack 2410.

In operation, laser diode array 2402 emits laser radiation which is collected and focused by focusing lens 2404. The light is then directed through the anti-reflective/high reflector coating 2406, which is anti-reflective with respect to the pump radiation, but is a high reflector with respect to the emitting radiation. The light then passes into gain medium 2408, which lases at the operating wavelength. All-optical switching mirror thin film stack 2410 is a thin film stack which may be, for example, the thin film stacks exemplified in Figures 20-22. The all-optical switching mirror thin

film stack 2410 serves to switch the oscillating coherent radiation out of the cavity. The all-optical switching mirror oscillates between a high reflectivity period in which the pulse builds up within the cavity and a low reflectivity in which the pulse is dumped or exits the cavity.

FIG. 25 shows a cross sectional view of a thin disk laser, containing an all-optical switching mirror thin film stack, according to the invention. Additional description of thin disk lasers generally is available from JENOPTIK, Inc. Thin disk laser 2500 includes high reflector 2502, gain medium 2504, optical fibers 2506, laser diode arrays 2508, all-optical switching mirror thin film stack 2510. Mirror substrate 2512, and heat sink 2514.

Gain medium 2504 has coated on one side high reflector 2502. On a side of high reflector 2502 opposite from the gain medium is located heat sink 2514. On a side of the gain medium opposite from the high reflector, but spaced apart from the gain medium is located mirror substrate 2512. On a side of the mirror substrate facing the gain medium is coated all-optical switching mirror thin film stack 2510. Directed into the cavity towards the gain medium are optical fibers 2506. Optically coupled to the optical fibers are laser diode arrays 2508.

In operation, laser light emitted by laser diode arrays 2508 is collected into optical fibers 2506. Light conducted through the optical fibers is then directed into the gain medium 2504, where pumped light is focused into the gain medium wherein the gain medium then emits its intrinsic operating wavelength. High reflector 2502 serves to define one end of the optical cavity. Heat sink 2514 conducts heat away from the gain medium and high reflector. Light exiting the gain medium is then directed to the all-optical switching mirror thin film stack 2510. The thin film stack oscillates between periods of high reflectivity and low reflectivity where during the high reflectivity state the optical pulse builds up within the cavity and during the low reflectivity stage the pulse is dumped from the cavity.

FIG. 26 shows a cross section of a fiber laser, containing an all-optical switching mirror thin film stack, according to the invention. Additional descriptions of fiber lasers generally can be obtained from Spectra Diode Labs (Santa Clara, CA). Fiber laser 2600 includes mirror substrate 2602, all-optical switching mirror thin film stack

2604, optical fiber 2608, mirror substrate 2610, focusing lens 2612, laser diode array 2614, and anti-reflective/highly reflective thin film stack 2616.

On an light emitting side of laser diode array 2614 is located focusing lens 2612. On a side of the focusing lens opposite from the laser diode array is located the anti-reflective/highly reflective thin film stack 2616, which is in turn coated on mirror substrate 2610, which is located on a side of the anti-reflective/highly reflective thin film stack opposite from the focusing lens. Located on the side of the mirror substrate opposite from the anti reflective/highly reflective thin film stack is optical fiber 2608. Located at an end of the optical fiber opposite from the anti-reflective/highly reflective thin film stack and mirror substrate is all-optical switching mirror thin film stack 2604, which is in turn coated upon mirror substrate 2602, located on a side of the all-optical switching mirror thin film stack opposite from the optical fiber. In operation, light is emitted by the laser diode array 2614, and is collected and focused by focusing lens 2612. Light is then passed through the anti-reflective/highly reflective thin film stack 2616 and further passes through mirror substrate 2610. The anti-reflective/highly reflective thin film stack serves as an anti-reflective coating for pumping light, and serves as a highly reflective coating with respect to emitted light. The light is then conducted along an optical fiber, which serves as a conductive path for the laser cavity. The laser light exits the optical fiber 2608 and is directed into all-optical switching mirror thin film stack 2604. The all-optical switching mirror thin film stacks serves to act as one end of the laser cavity in the high reflectivity state, thereby allowing the pulse to build up to maximum intensity and the all-optical switching mirror then switches to the low-reflectivity state which allows the pulse to exit the cavity.

FIG. 27 shows a cross-section through a monolithic passive cavity dumped laser, according to the invention. Laser 2700 includes diffractive element 2702, undoped sapphire ends 2704, reflector 2706, laser diode arrays 2708, gain medium 2710, and all-optical switching mirror thin film stack 2712.

Gain medium 2710 possesses a distal and a proximal end. At both of these ends are located undoped sapphire ends 2704, which are attached to the gain medium. In a preferred embodiment, the undoped sapphire ends are attached to the gain medium by diffusion bonding. This diffusion bonding can be performed by Onyx Optics (Pleasanton, California). Surrounding the gain medium are laser diode arrays 2708. On

a side of the laser diode arrays opposite from the gain medium are located reflectors 2706. At the proximal end of the undoped sapphire end, which is located at the proximal end of the gain medium, is located diffractive element 2702. In a preferred embodiment, the diffractive element is etched onto the end of the undoped sapphire end located at the proximal end of the gain medium. At the distal end of the undoped sapphire end located at the distal end of the gain medium is all-optical switching mirror thin film stack 2712.

In operation the laser diode arrays 2708 serve to pump gain medium 2710. Radiation that is directed away from the gain medium is reflected by reflectors 2706 towards the gain medium. Undoped sapphire ends 2704 serve a variety of functions, including being spacers, heat sinks, and being used to reduce absorption of light when using a three-level (ytterbium) system. While the undoped sapphire ends are preferable when constructing a three-level system, they are not required for a four-level system. Additionally, the undoped sapphire ends may be preferrable when a lattice match for growing single crystal CdTe or other single crystals are desired.

Diffractive element 2702 also serves a variety of functions, including aberration correction, generation of a top-hat spatial distribution, and serving as a mode-selecting device. Diffractive elements suitable for practicing the invention may be obtained from Wavelength Sciences, Inc., and from Gray Process, Inc. Additional information may be found in James R. Leger et al., Diffractive Optical Elements for Mode Shaping of a Nd:YAG Laser, Optics Letters **19**:108-110 (1994) (concerning mode suppression, top hat generation and aberration correction). The aberration correction function of the diffractive element may be primarily correcting the thermal aberrations in the system that cause astigmatism in the beam. The top hat generation function serves to modify the spatial output profile of the beam from Gaussian to a top hat distribution, where the energy is virtually of even distribution from the center to the outside edge of the beam. Of course, in some embodiments, other spatial distributions, such as a doughnut distribution, as discussed above, may be desirable. Additionally, this spatial distribution correction may not be necessary if a gaussion distribution is desired. The mode suppressor functions such that it has little to no loss for the fundamental mode, but a 50% or higher mode loss for higher order modes. In this way, the mode suppressor functions to suppress the higher order modes.

All-optical switching mirror thin film stack 2712 serves to switch the oscillating coherent radiation out of the cavity. The all-optical switching thin film stack oscillates between a high reflectivity period in which the pulse builds up within the cavity, and a low reflectivity period in which the pulse is dumped, or exits the cavity.

An advantage of a monolithic laser like this is greatly increased robustness, compared to traditional laser desings. A monolithic design will not be as susceptible to environmental changes, such as vibration or temperature, as conventional, mechanically fastened, designs.

FIG.28 shows a cross-section of a laser, according to the invention, with specific emphasis on the flex circuit assembly providing power to the diode array. Shown in laser 2800 are laser rod 2802, flow tube 2804, laser diodes 2806, heat sink/conductor layer 2808, heat sink with insulator layer 2810, flex circuit 2812, anode layer 2814, cathode layer 2816, electrical contact surface 2818, reflector surface 2820, and coolant channel 2822.

Surrounding laser rod 2802 is flow tube 2804. Surrounding the flow tube is coolant channel 2822. Surrounding the coolant channel is reflector surface 2820. Surrounding the reflector surface is heat sink/conductor layer 2808. Contained within the heat sink/conductor layer are laser diodes 2806, of which 10 are shown. The laser diodes are aligned with openings in the reflector layer. Surrounding the heat sink/ conductor layer is heat sink with insulator layer 2810. Coupled to the heat sink/ conductor layer is flex circuit 2812. The flex circuit contains an anode layer 2814, and a cathode layer 2816. On a side of the laser diode array assembly opposite from the flex circuit is located electrical contact surface 2818.

In operation, anode layer 2814, and cathode layer 2816, of flex circuit 2812 serve to carry current to the heat sink/conductor layer 2808. In a preferrable embodiment, the flex circuit has both the anode layer and the cathode layer incorporated into one monolithic film structure. In a more preferrable embodiment, the flex circuit is a double sided, coated KAPTON film. Electrical current is conducted through the heat sink/conductor layer to the laser diodes 2806, which emit light so as to pump the laser rod 2802. The electrical circuit is completed by the coupling of electrical contact surfaces 2818. Heat generated during the pumping of the laser rod is conducted away from the laser rod through the cooperative action of flow tube 2804, coolant channel

2822 (which contains a coolant media), heat sink insulator layer 2810, and the action of heat sink/conductor layer 2808. Reflector surface 2820 serves to re-reflect laser light emitted by the laser diodes that is reflected away from the rod, thus increasing pump efficiency. The double sided clamshell flex circuit envisaged herein offers a number of advantages over conventional designs, including low cost, using less "real estate" of the reflector surface, and ease of assembly.

FIG. 29 shows a cross-section of a rod and flow tube end block assembly, i.e. an integrated binder bolt system, according to the invention. Shown in assembly 2900 are coolant inlet 2902, bolt 2904, rod end plate/O-ring compressor 2906, flow tube end plate/O-ring compressor 2908, end-block body 2910, flow tube end plate/integral standoff 2912, flow tube O-ring seal 2914, rod O-ring seal 2916, flow tube 2918, laser rod 2920, and coolant exit 2922.

Laser rod 2920 penetrates perpendicularly through flow tube end plate/O-ring compressor 2908. Surrounding the rod is flow tube 2918, which together with the rod forms coolant exit 2922. Coolant exit 2922 communicates with coolant inlet 2902, to form a path for coolant fluid through a laser assembly. End block body 2910, which includes coolant inlet 2902, is positioned against the flow tube end plate/O-ring compressor. A fluid seal is formed by flow tube O-ring seal 2914. Flow tube end plate integral standoff 2912 are secured the flow tube end plate/O-ring compressor and contain internal threads. The end block body is positioned against the flow tube end plate/O-ring compressor by the cooperative action of the flow tube end plate integral standoffs, the rod, and through holes 2924 which penetrate through the body of the end block body. The end block body is secured against the flow tube end plate/O-ring compressor by the action of the rod end plate/O-ring compressor 2906 and bolts 2904. A fluid seal is formed by the action of rod O-ring seal 2916.

In operation the end block body 2910 serves to create a flow channel having at one end coolant inlet 2902, and at the other end coolant exit 2922, which is formed by the annular cooperation of flow tube 2918 and laser rod 2920. Flow tube O-ring seal 2914 serves to create a fluid seal to prevent leakage between the end lock body and flow tube end plate/O-ring compressor 2908. Flow tube end plate integral standoffs 2912 serve to locate the end block body, and also contain internal threads allowing attachment of rod end plate/O-ring compressor 2906, through the attaching action of

bolts 2904. Rod O-ring seal 2916 create a fluid seal at the intersection of the end block body and the rod end plate/O-ring compressor, thus preventing leaks from this area. The rod end plate/O-ring compressor and the flow tube end plate/O-ring compressor function to secure the end block and the rod. Additionally, the endplates are machined so as to be relatively thin, thus reducing the need to lengthen the rod to accomodate thicker end plates.

The advantage of the inventive integrated binder bolt system is that provides a way of mating the rod and cooling system without needing to lengthen the rod, thus increasing the optical path length. Avoiding lengthening the rod length is an especially attractive feature of this design, as the index of the rod material is so high (approximately 1.92 in some embodiments). An additional advantage is that the end plates and the end block body may be made using metal injection molding, to reduce cost and improve performance.

In a preferrable embodiment, laser rod 2920 and flow tube 2918 may be secured into place using an adhesive. For example, the rod and the flow tube may be secured using an epoxy adhesive delivered into place through the water channel using a needle. Capillary action may draw the epoxy down the rod or the flow tube into the insertion point in the metal assembly. This is advantageous because it results in a compact system, and short optical path length.

FIG. 30 is a cross-sectional view of another embodiment of the laser. Here, the gain medium 16 is pumped by a pump source 22 through optical fibers 82 coupled to the gain medium 16. The gain medium 16 is cooled by a flow tube 84. The gain medium 16 is also surrounded by a reflector 38.

FIG. 31 is a side view of one embodiment of a corrector plate 86 with a gray process surface.

FIG. 32 is a side view of another embodiment of a corrector plate 88 with an aspheric surface.

FIG. 33 is a schematic of a laser system for removing material from a substrate. A substrate holder 102 holds the substrate 104 for cutting by the laser 100. The substrate holder 102 may be a conventional tape system, a conventional vacuum chuck or an electrostatic chuck. The electrostatic chuck operates on the principle of static attraction, and is preferably manufactured using single crystal sapphire. While

electrostatic chucks are known per se, they have not been used to date in dicing operations, because the mechanical saws currently used for dicing would cut the expensive sapphire chuck into small pieces.

By contrast, the inventive laser cutting system does not substantially cut the sapphire electrostatic chuck, because the sapphire is transparent to wavelengths of laser light that can be used to cut silicon. Such a system offers the advantages of reduced contamination, and lower operating costs.

The laser 100 is mounted on a gantry 106. The gantry 106 may be coupled to a positioning device 108 which moves the laser 100 relative to the substrate 104. This provides a non-contact process, which substantially reduces vibration issues in cutting operations, such as dicing. Alternatively, the substrate holder 102 may be coupled to a positioning device 108 which moves the substrate 104 relative to the laser 100. Consequently, the inventive methods and apparatus encompass positioning the substrate with respect to the stream of light pulses by moving the substrate. Alternatively, the inventive methods and apparatus encompass positioning the stream of light pulses with respect to the substrate by redirecting the stream of light pulses.

The positioning device 108 may be coupled to a controller 110. The controller 110 may be coupled to a feedback device 112. The feedback device 112 may be a charge-coupled device (CCD) camera with high-magnification optics. Preferably the feedback device 112 is a pattern recognition system, which is able to scan the wafer to locate the fiducials, and locate the streets to direct the cutting, available from Adept Technology, Milpitas, California. The controller 110 may also contain user controls 114 for programming the controller 110. A vacuum pick-up 120 coupled to the nozzle 118 picks up debris produced by the laser 100.

FIG. 34 is a side view of a laser system showing a vacuum pick-up. A gas jet 116 is passed into the nozzle 118 and over the focusing optics 34 to the nozzle 118 and focusing optics 34 clear of debris. Most of the debris will be removed by the shock wave caused by the laser pulses.

Besides high-precision cutting, this laser system is useful for milling, or reaching buried circuit layers. This laser system is also useful for high-precision drilling, such as for inkjet heads or fuel injector nozzles. This laser system may also be

used for surface processing, such as to harden polymers and metals, and to apply a stain-resistant treatment to carpeting.

The foregoing description of the preferred embodiments of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Obviously, many modifications and variations will be apparent to practitioners skilled in this art. It is intended that the scope of the invention be defined by the following claims and their equivalents.

WHAT IS CLAIMED IS:

1. A laser, comprising:

a resonator cavity including an optical path;

a gain medium positioned in the resonator cavity along the optical path;

an electro-optic device positioned in the resonator along the optical path;

a polarizer positioned in the resonator cavity along the optical path;

a pump source generating a pump beam incident on the gain medium to produce an intracavity beam that is incident on a surface of the polarizer to produce a polarized output beam, wherein the polarized output beam has an average power of at least 40 W; and

a high voltage pulser coupled to the electro-optic device and generating a voltage pulse to the electro-optic device, wherein the polarized output beam has a pulsewidth which does not exceed 1.5 nanoseconds with a pulse repetition frequency of at least 100 kHz.

2. The laser of claim 1, wherein the resonator cavity has a length selected to produce a pulsewidth that does not exceed 1.5 nanoseconds.

3. The laser of claim 1, wherein the resonator cavity has a length not exceeding nine inches.

4. The laser of claim 1, wherein the resonator cavity has a length not exceeding six inches.

5. The laser of claim 1, wherein the resonator cavity has a length not exceeding three inches.

6. The laser of claim 1, wherein the gain medium is a birefringent material.

7. The laser of claim 1, wherein the gain medium is selected from $Nd:YAlO_3$, $Nd:YVO_4$, and Nd:YLF.

8. The laser of claim 1, wherein the gain medium is $Nd:YAlO_3$.

9. The laser of claim 1, wherein the gain medium has an anti-reflective surface.

10. The laser of claim 9, wherein the anti-reflective surface is a sub-wavelength structure.

11. The laser of claim 1, wherein the electro-optic device is a material which exhibits minimal ringing at frequencies above 100 kHz.

12. The laser of claim 1, wherein the electro-optic device is selected from BBO, KTP, and RTA.

13. The laser of claim 1, wherein the electro-optic device is BBO.

14. The laser of claim 1, wherein a distance between the electro-optic device and the high voltage pulser is minimized.

15. The laser of claim 1, wherein the electro-optic device has a high aspect ratio.

16. The laser of claim 15, wherein the high aspect ratio of the electro-optic device is sufficient to reduce a voltage required to induce birefringence in the electro-optic device.

17. The laser of claim 1, wherein the electro-optic device contains a channel to reduce a voltage required to induce birefringence in the electro-optic device.

18. The laser of claim 1, wherein the polarizer is a thin film polarizer.

19. The laser of claim 1, wherein the polarizer is a birefringent polarizer.

20. The laser of claim 1, wherein the polarizer is a binary surface.

21. The laser of claim 1, wherein the pump source is sufficient to produce a polarized output beam of at least 40 W.

22. The laser of claim 1, wherein the pump source is a diode source.

23. The laser of claim 1, wherein the pump source is at least one diode bar.

24. The laser of claim 1, wherein the pump source is at least one vertically-emitting diode array.

25. The laser of claim 1, wherein the pump source is a plurality of aluminum-free diodes.

26. The laser of claim 1, wherein the pump source is configured to side pump the gain medium.

27. The laser of claim 1, wherein the pump source is positioned radially symmetrically around the gain medium.

28. The laser of claim 1, wherein a profile of the pump beam substantially matches a mode volume of the gain medium.

29. The laser of claim 1, further comprising a focusing device positioned between the pump source and the gain medium.

30. The laser of claim 1, wherein the pump source is fiber coupled to the gain medium.

31. The laser of claim 1, wherein the polarized output beam is near diffraction limited.

32. The laser of claim 31, wherein the polarized output beam has an M^2 of less than 5.

33. The laser of claim 31, wherein the polarized output beam has an M^2 of less than 2.

34. The laser of claim 31, wherein the polarized output beam has an M^2 of less than 1.5.

35. The laser of claim 1, wherein the polarized output beam is single mode.

36. The laser of claim 1, wherein the high voltage pulser includes at least one step recovery diode.

37. The laser of claim 1, wherein the high voltage pulser includes at least one drift step recovery diode.

38. The laser of claim 37, wherein the high voltage pulser includes at least one silicon avalanche shaper coupled to the at least one drift step recovery diode.

39. The laser of claim 1, wherein the high voltage pulser includes at least one step recovery transistor.

40. The laser of claim 1, wherein the high voltage pulser includes at least one drift step recovery transistor.

41. The laser of claim 40, wherein the high voltage pulser includes at least one silicon avalanche shaper coupled to the at least one drift step recovery transistor.

42. The laser of claim 1, wherein the high voltage pulser includes at least one field effect transistor.

43. The laser of claim 1, wherein the high voltage pulser includes at least one avalanche diode.

44. The laser of claim 1, wherein the high voltage pulser includes at least one light activated silicon switch.

45. The laser of claim 1, wherein the high voltage pulser includes at least one photo-conductive switch.

46. The laser of claim 1, further comprising an aberration correcting device positioned in the resonator along the optical path, the aberration correcting device including an aberration correcting surface.

47. The laser of claim 46, wherein the aberration correcting surface is a binary surface.

48. The laser of claim 46, wherein the aberration correcting surface is a gray process surface.

49. The laser of claim 46, wherein the aberration correcting surface is an aspheric surface.

50. The laser of claim 46, wherein the aberration correcting surface is a spherical surface on a graded-index material.

51. The laser of claim 46, wherein the aberration correcting surface further provides focusing of the intracavity beam.

52. The laser of claim 1, further comprising an aberration correcting device positioned outside of the resonator along the optical path, the aberration correcting device including an aberration correcting surface.

53. The laser of claim 1, further comprising:

a focusing device positioned in the resonator along the optical path, the focusing device including a focusing surface.

54. The laser of claim 53, wherein the focusing surface is a binary surface.

55. The laser of claim 53, wherein the focusing surface is a gray process surface.

56. The laser of claim 53, wherein the focusing surface is an aspheric surface.

57. The laser of claim 1, further comprising:

a mode selection device positioned in the resonator along the optical path, the mode selection device including a mode selecting surface.

58. The laser of claim 57, wherein the mode selecting surface is a binary surface.

59. The laser of claim 57, wherein the mode selecting surface is a grey process surface.

60. The laser of claim 1, further comprising a collimating device positioned in the resonator along the optical path, the collimating device including a collimating surface.

61. The laser of claim 60, wherein the collimating surface is a binary surface.

62. The laser of claim 60, wherein the collimating surface is a gray process surface.

63. The laser of claim 60, wherein the collimating surface is an aspheric surface.

64. The laser of claim 1, further comprising a pulse sharpener.

65. The laser of claim 64, wherein the pulse sharpener is a solid state pulse sharpener, or a magnetic pulse sharpener.

66. A laser system, comprising:

a resonator cavity including an optical path;

a gain medium positioned in the resonator cavity along the optical path;

an electro-optic device positioned in the resonator along the optical path;

a polarizer positioned in the resonator cavity along the optical path;

a pump source generating a pump beam incident on the gain medium to produce an intracavity beam that is incident on a surface of the polarizer to produce a polarized output beam;

an amplifier coupled to the resonator cavity and amplifying the polarized output beam to provide an amplified polarized output beam of 40 W or greater; and

a high voltage pulser coupled to the electro-optic device and generating a voltage pulse to the electro-optic device, wherein the amplified polarized output beam has a pulsewidth which does not exceed 1.5 nanoseconds with a pulse repetition frequency of at least 100 kHz.

67. A laser system for removing material from a substrate, comprising:

a resonator cavity including an optical path;

a gain medium positioned in the resonator cavity along the optical path;

an electro-optic device positioned in the resonator along the optical path;

a polarizer positioned in the resonator cavity along the optical path;

a pump source generating a pump beam incident on the gain medium to produce an intracavity beam that is incident on a surface of the polarizer to produce a polarized output beam, wherein the polarized output beam has an average power of at least 40 W;

a high voltage pulser coupled to the electro-optic device and generating a voltage pulse to the electro-optic device, wherein the polarized output beam has a pulsewidth which does not exceed 1.5 nanoseconds at a pulse repetition frequency of at least 100 kHz; and

a substrate holder for holding and positioning the substrate in a path of the polarized output beam.

68. The system of claim 67, further comprising a positioning device for positioning the polarized output beam and substrate holder relative to each other;

69. The system of claim 68, further comprising a controller coupled to the positioning device.

70. The system of claim 67, further comprising a depolarizing device positioned in the path of the polarized output beam to depolarize the polarized output beam.

71. The system of claim 67, wherein the resonator cavity has a length selected to produce a pulsewidth that does not exceed 1.5 nanoseconds.

72. The system of claim 67, wherein the resonator cavity has a length not exceeding nine inches.

73. The system of claim 67, wherein the resonator cavity has a length not exceeding six inches.

74. The system of claim 67, wherein the resonator cavity has a length not exceeding three inches.

75. The system of claim 67, wherein the gain medium is a birefringent material.

76. The system of claim 67, wherein the gain medium is selected from $Nd:YAlO_3$, $Nd:YVO_4$, and Nd:YLF.

77. The system of claim 67, wherein the gain medium is $Nd:YAlO_3$.

78. The system of claim 67, wherein the gain medium has an anti-reflective surface.

79. The system of claim 78, wherein the anti-reflective surface is a sub-wavelength structure.

80. The system of claim 67, wherein the electro-optic device is a material which exhibits minimal ringing at frequencies above 100 kHz.

81. The system of claim 67, wherein the electro-optic device is selected from BBO, KTP, and RTA.

82. The system of claim 67, wherein the electro-optic device is BBO.

83. The system of claim 67, wherein a distance between the electro-optic device and the high voltage pulser is minimized.

84. The system of claim 67, wherein the electro-optic device has a high aspect ratio.

85. The system of claim 84, wherein the high aspect ratio of the electro-optic device is sufficient to reduce a voltage required to induce birefringence in the electro-optic device.

86. The system of claim 67, wherein the electro-optic device contains a channel to reduce a voltage required to induce birefringence in the electro-optic device.

87. The system of claim 67, wherein the polarizer is a thin film polarizer.

88. The system of claim 67, wherein the polarizer is a birefringent polarizer.

89. The system of claim 67, wherein the polarizer is a binary surface.

90. The system of claim 67, wherein the pump source is sufficient to produce a polarized output beam of at least 40 W.

91. The system of claim 67, wherein the pump source is a diode source.

92. The system of claim 67, wherein the pump source is at least one diode bar.

93. The system of claim 67, wherein the pump source is at least one vertically-emitting diode array.

94. The system of claim 67, wherein the pump source is a plurality of aluminum-free diodes.

95. The system of claim 67, wherein the pump source is configured to side pump the gain medium.

96. The system of claim 67, wherein the pump source is positioned radially symmetrically around the gain medium.

97. The system of claim 67, wherein a profile of the pump beam substantially matches a mode volume of the gain medium.

98. The system of claim 67, further comprising a focusing device positioned between the pump source and the gain medium.

99. The system of claim 67, wherein the pump source is fiber coupled to the gain medium.

100. The system of claim 67, wherein the polarized output beam is near diffraction limited.

101. The system of claim 100, wherein the polarized output beam has an M^2 of less than 5.

102. The system of claim 100, wherein the polarized output beam has an M^2 of less than 2.

103. The system of claim 100, wherein the polarized output beam has an M^2 of less than 1.5.

104. The system of claim 67, wherein the polarized output beam is single mode.

105. The system of claim 67, wherein the high voltage pulser includes at least one step recovery diode.

106. The system of claim 67, wherein the high voltage pulser includes at least one drift step recovery diode.

107. The system of claim 106, wherein the high voltage pulser includes at least one silicon avalanche shaper coupled to the at least one drift step recovery diode.

108. The system of claim 67, wherein the high voltage pulser includes at least one step recovery transistor.

109. The system of claim 67, wherein the high voltage pulser includes at least one drift step recovery transistor.

110. The system of claim 109, wherein the high voltage pulser includes at least one silicon avalanche shaper coupled to the at least one drift step recovery transistor.

111. The system of claim 67, wherein the high voltage pulser includes at least one field effect transistor.

112. The system of claim 67, wherein the high voltage pulser includes at least one avalanche diode.

113. The system of claim 67, wherein the high voltage pulser includes at least one light activated silicon switch.

114. The system of claim 67, wherein the high voltage pulser includes at least one photo-conductive switch.

115. The system of claim 67, further comprising an aberration correcting device positioned in the resonator along the optical path, the aberration correcting device including an aberration correcting surface.

116. The system of claim 115, wherein the aberration correcting surface is a binary surface.

117. The system of claim 115, wherein the aberration correcting surface is a gray process surface.

118. The system of claim 115, wherein the aberration correcting surface is an aspheric surface.

119. The system of claim 115, wherein the aberration correcting surface is a spherical surface on a graded-index material.

120. The system of claim 115, wherein the aberration correcting surface further provides focusing of the intracavity beam.

121. The system of claim 67, further comprising an aberration correcting device positioned outside of the resonator along the optical path, the aberration correcting device including an aberration correcting surface.

122. The system of claim 67, further comprising:

a focusing device positioned in the resonator along the optical path, the focusing device including a focusing surface.

123. The system of claim 122, wherein the focusing surface is a binary surface.

124. The system of claim 122, wherein the focusing surface is a gray process surface.

125. The system of claim 122, wherein the focusing surface is an aspheric surface.

126. The system of claim 67, further comprising:

a mode selection device positioned in the resonator along the optical path, the mode selection device including a mode selecting surface.

127. The system of claim 126, wherein the mode selecting surface is a binary surface.

128. The system of claim 126, wherein the mode selecting surface is a grey process surface.

129. The system of claim 67, further comprising a collimating device positioned in the resonator along the optical path, the collimating device including a collimating surface.

130. The system of claim 129, wherein the collimating surface is a binary surface.

131. The system of claim 129, wherein the collimating surface is a gray process surface.

132. The system of claim 129, wherein the collimating surface is an aspheric surface.

133. The system of claim 67, further comprising an amplifier coupled to the resonator cavity and amplifying the polarized output beam to provide an amplified polarized output beam of 40 W or greater.

134. A laser system for surface processing, comprising:

the system of claim 67; and

a mounting device for mounting and positioning the surface in a path of the polarized output beam so that the surface can be processed.

135. A laser system for milling material, comprising:

the system of claim 67; and

a mounting device for mounting and positioning the material in a path of the polarized output beam so that the material can be milled.

136. A laser, comprising:

a resonator cavity including an optical path;

a gain medium positioned in the resonator cavity along the optical path;

an all-optical switching mirror positioned at an end of the resonator cavity;

a laser diode pump source generating a pump beam incident on the gain medium to produce an intracavity beam that is incident on a surface of the all-optical switching mirror to produce an output beam.

137. The laser of claim 137, wherein the all-optical switching mirror comprises a distributed feedback thin film stack, a Fabry-Perot thin film stack, or a hybrid distributed feedback/Fabry-Perot thin film stack.

138. The laser of claim 137, wherein the all-optical switching mirror comprises at least one layer of non-linear material.

139. The laser of claim 139, wherein the non-linear material is cadmium telluride (CdTe).

140. The laser of claim 137, wherein the all-optical switching mirror comprises at least one layer of Al_2O_3.

141. The laser of claim 137, wherein an end of the resonator comprises a diffractive mirror.

142. The laser of claim 142, wherein the diffractive mirror comprises an aberration corrector, a top hat generator, or a mode selector, and combinations thereof.

143. The laser of claim 143, wherein the diffractive mirror comprises an aberration corrector.

144. The laser of claim 143, wherein the diffractive mirror comprises a top hat generator.

145. The laser of claim 143, wherein the diffractive mirror comprises a mode selector.

146. The laser of claim 137, wherein the laser is configured in a monolithic design.

147. The laser of claim 137, wherein ends of the gain medium are undoped.

148. The laser of claim 137, wherein ends of the gain medium are doped.

149. The laser of claim 137, wherein the laser is configured in a micro-chip design.

150. The laser of claim 137, wherein the laser is configured in a thin disk design.

151. The laser of claim 137, wherein the laser is configured in a fiber laser design.

152. The laser of claim 137, wherein the laser possesses a contrast ratio of at least about 9:1.

153. The laser of claim 137, wherein the laser possesses a contrast ratio of at least about 10:1.

154. The laser of claim 137, wherein the laser produces an average power of more than about ten watts.

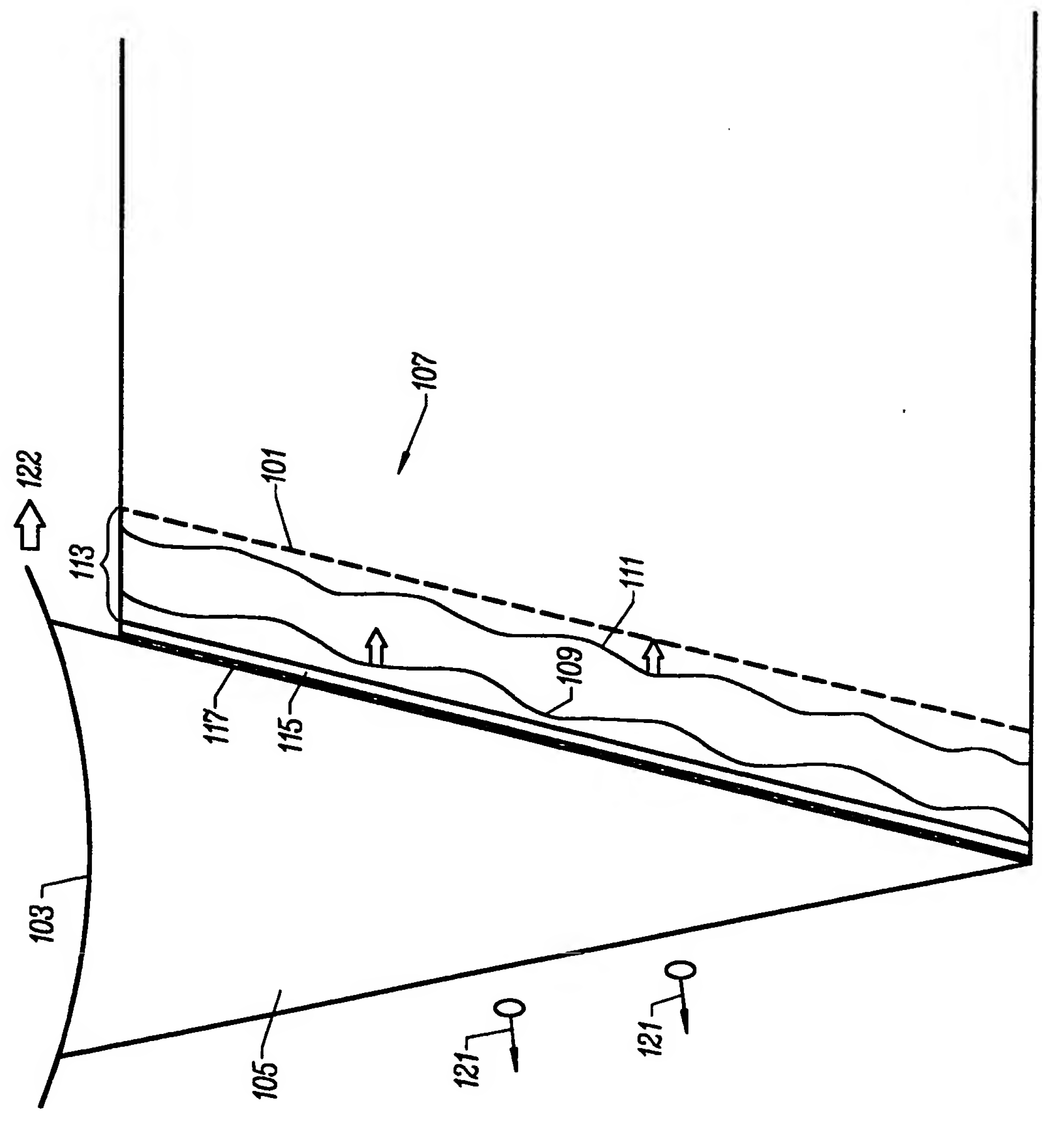


FIG. 1

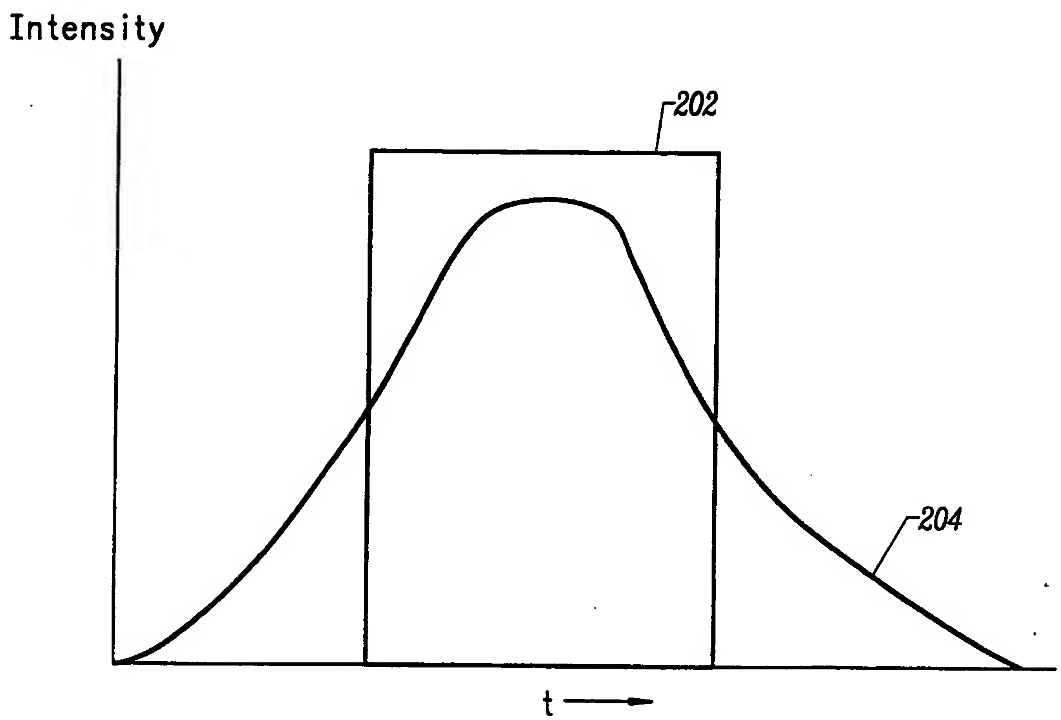


FIG. 2

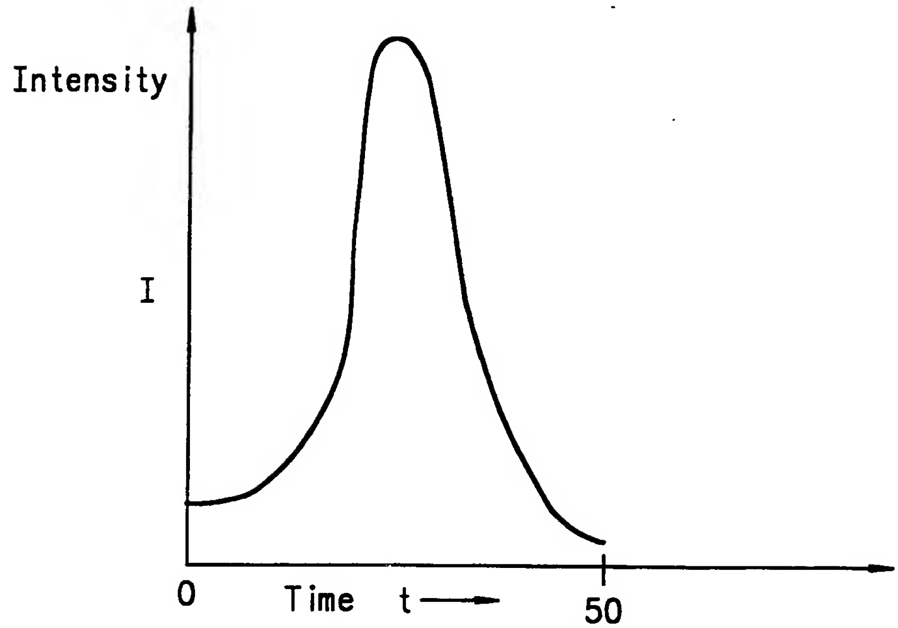


FIG. 3A

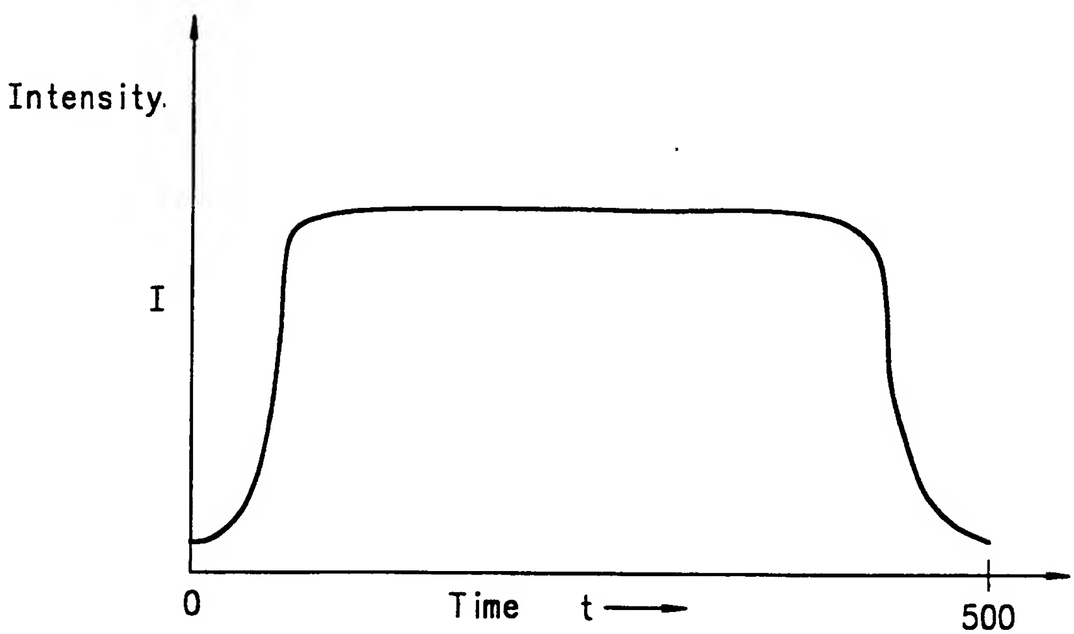


FIG. 3B

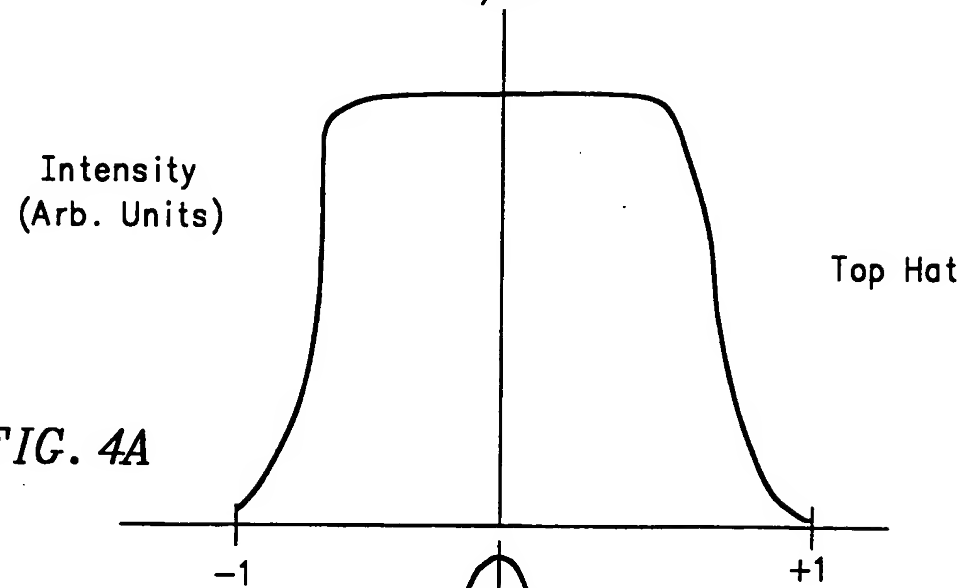


FIG. 4A

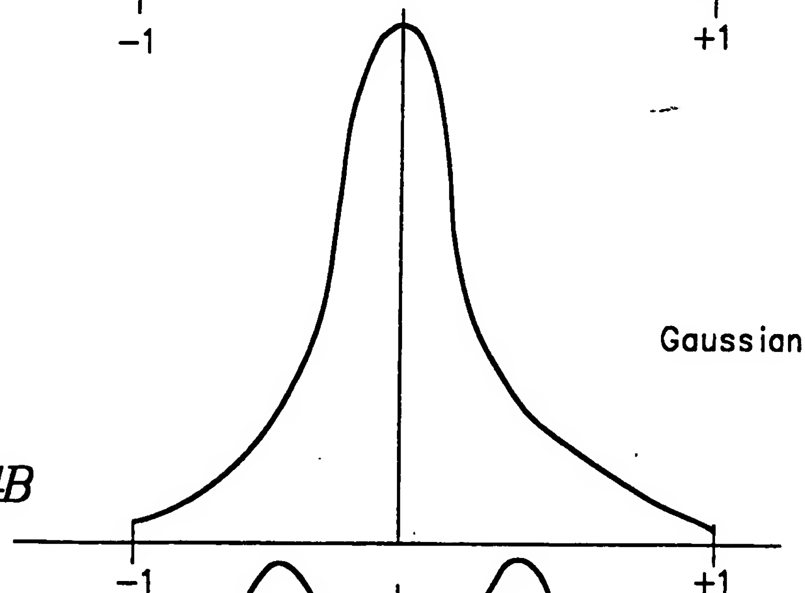


FIG. 4B

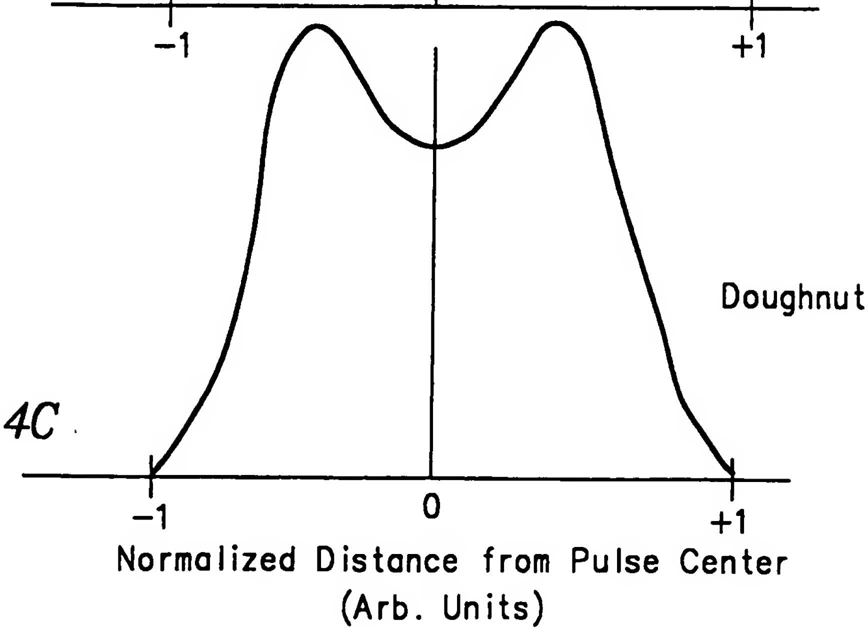


FIG. 4C

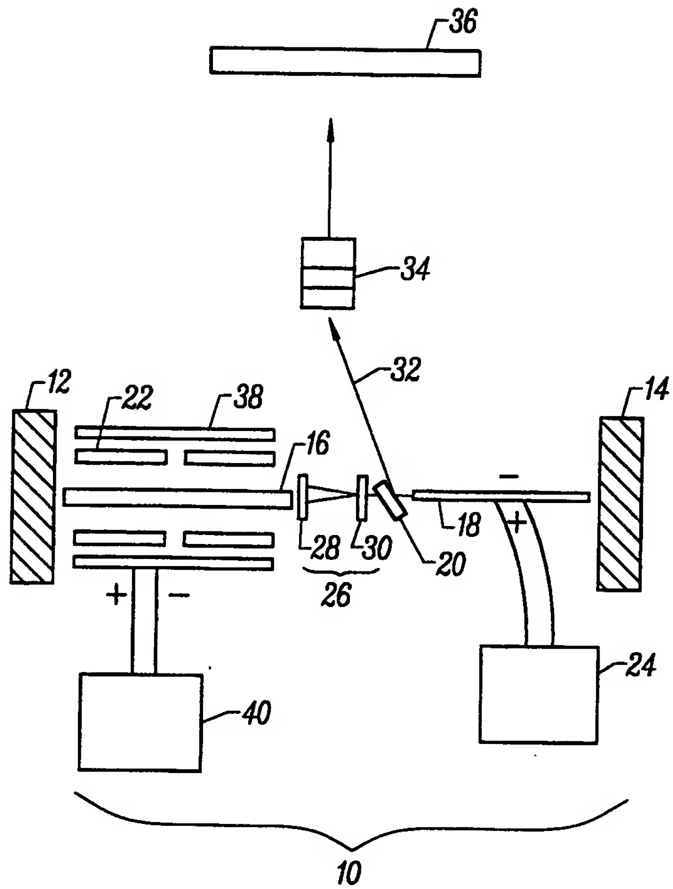


FIG. 5

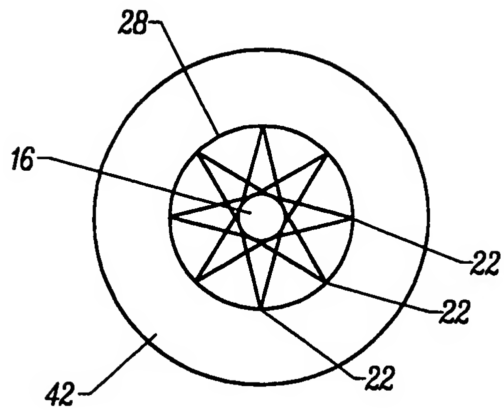


FIG. 6

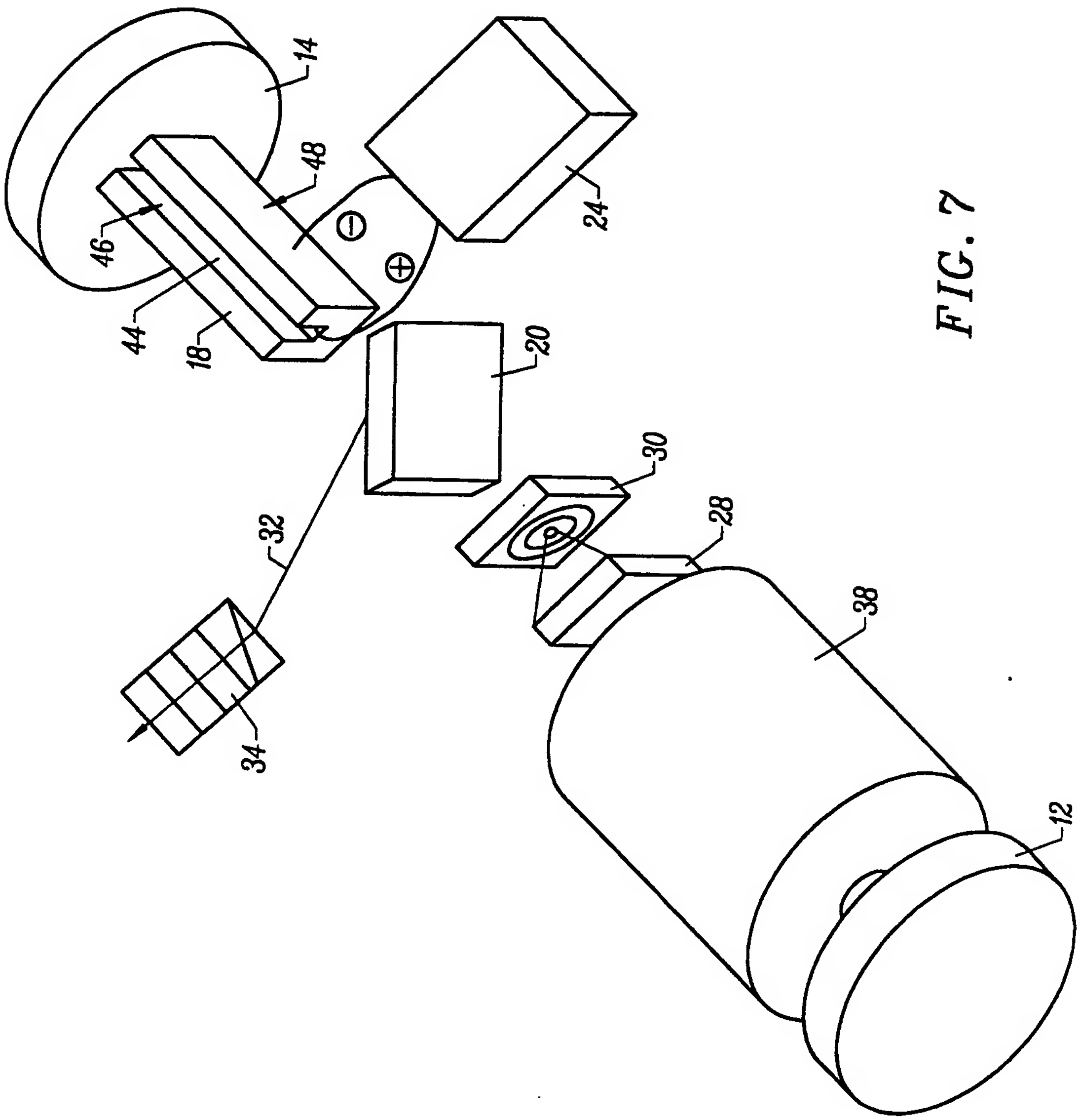


FIG. 7

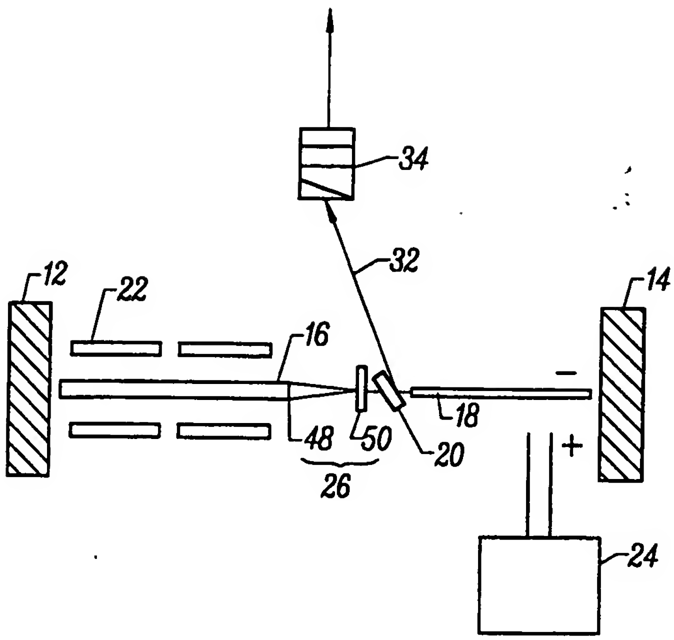


FIG. 8

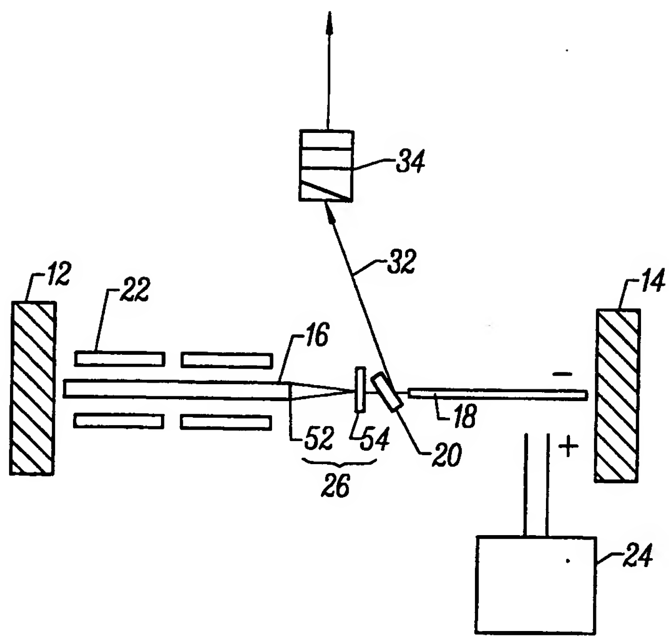


FIG. 9

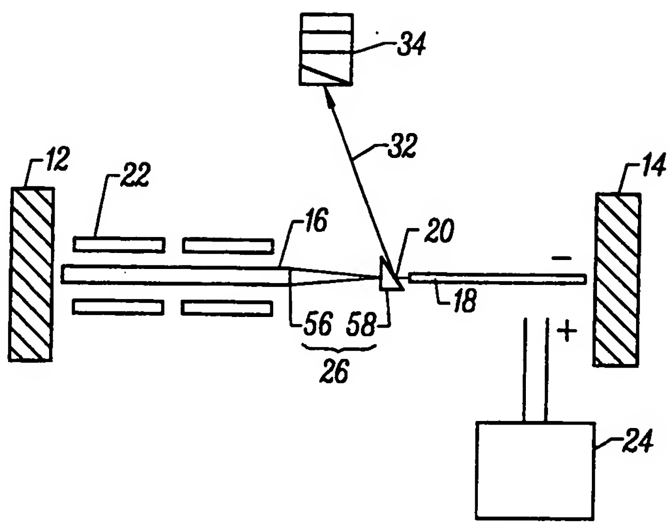


FIG. 10

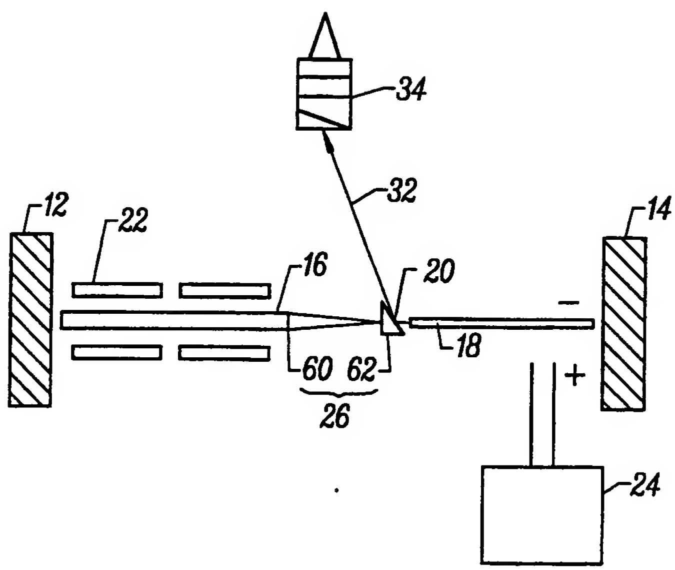


FIG. 11

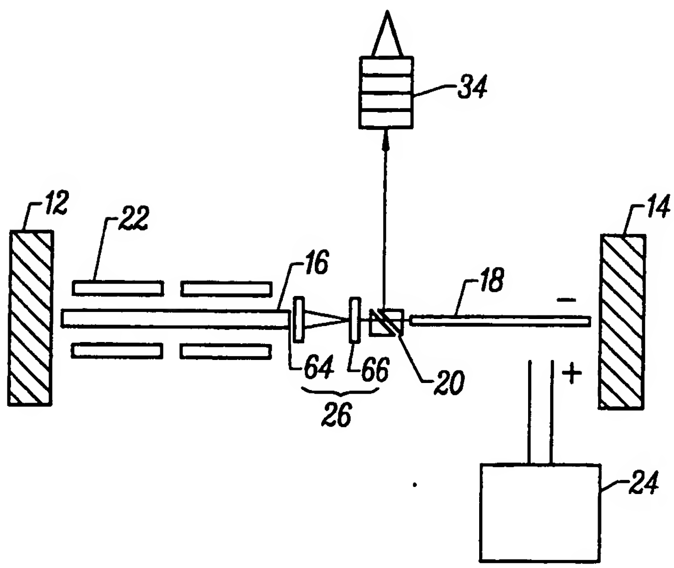


FIG. 12

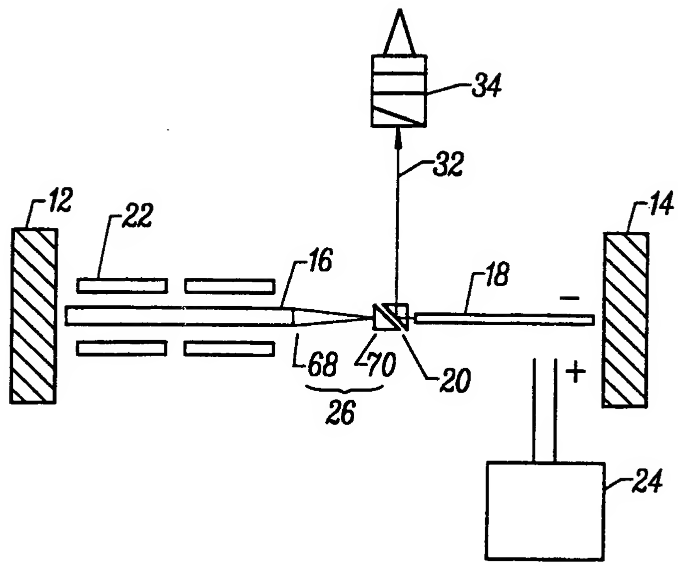


FIG. 13

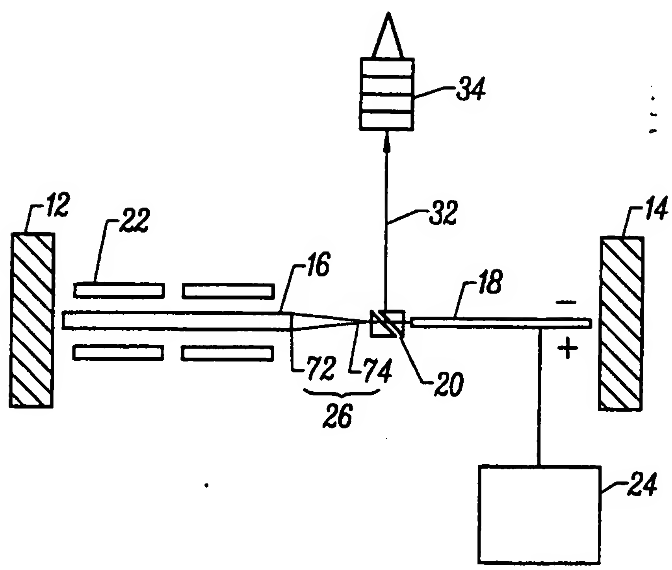


FIG. 14

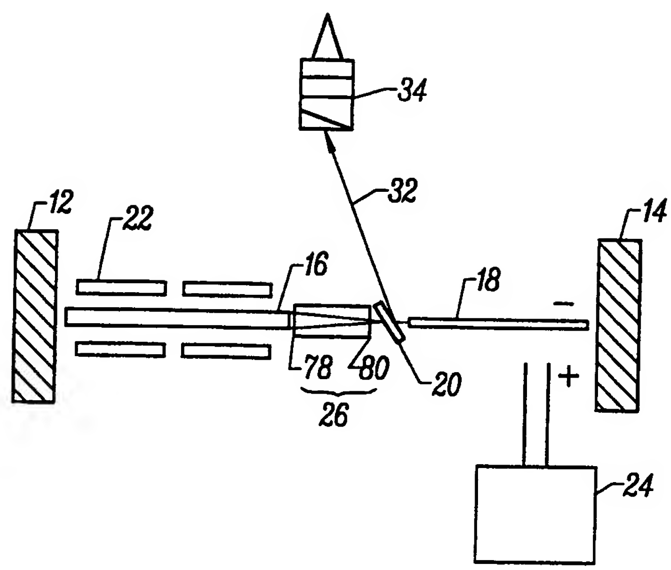


FIG. 15

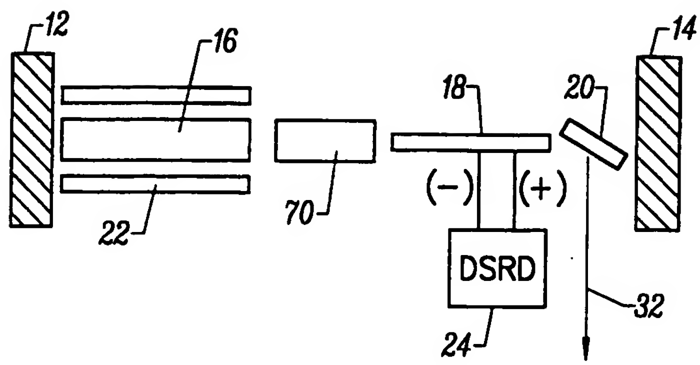


FIG. 16

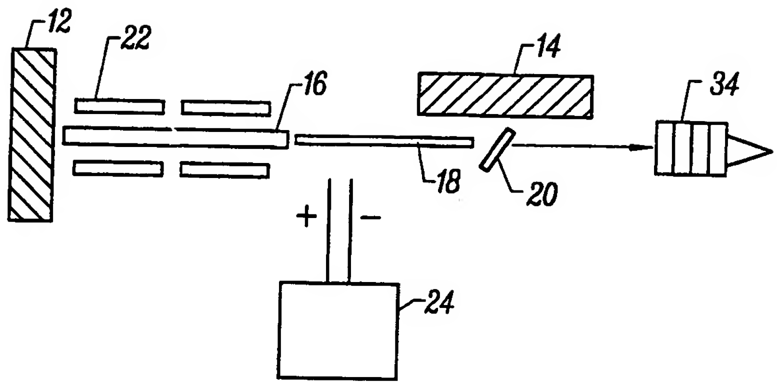


FIG. 17

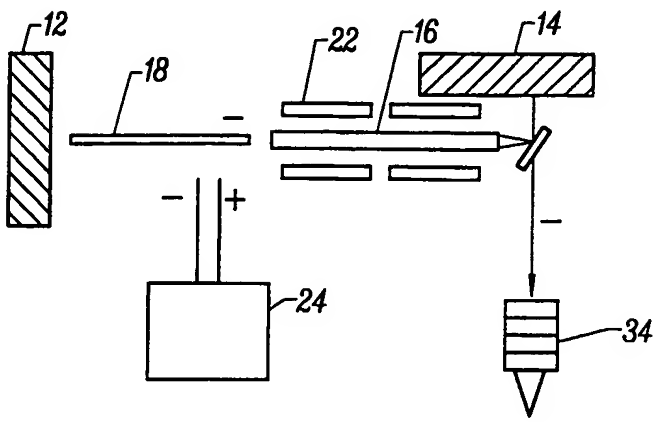


FIG. 18

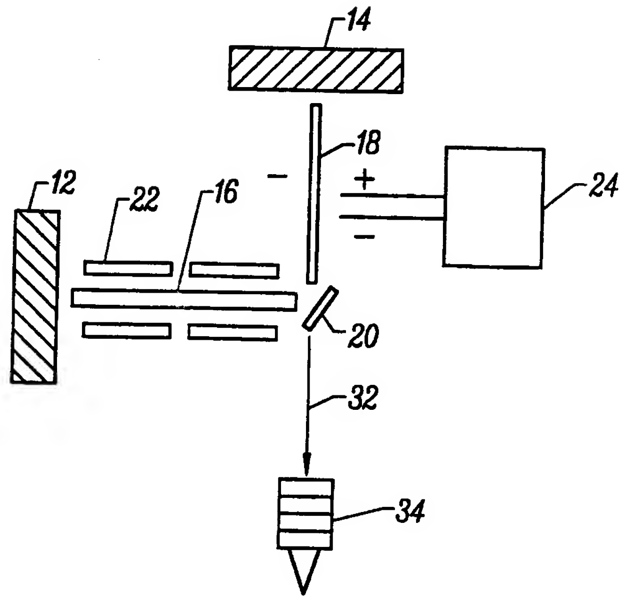


FIG. 19

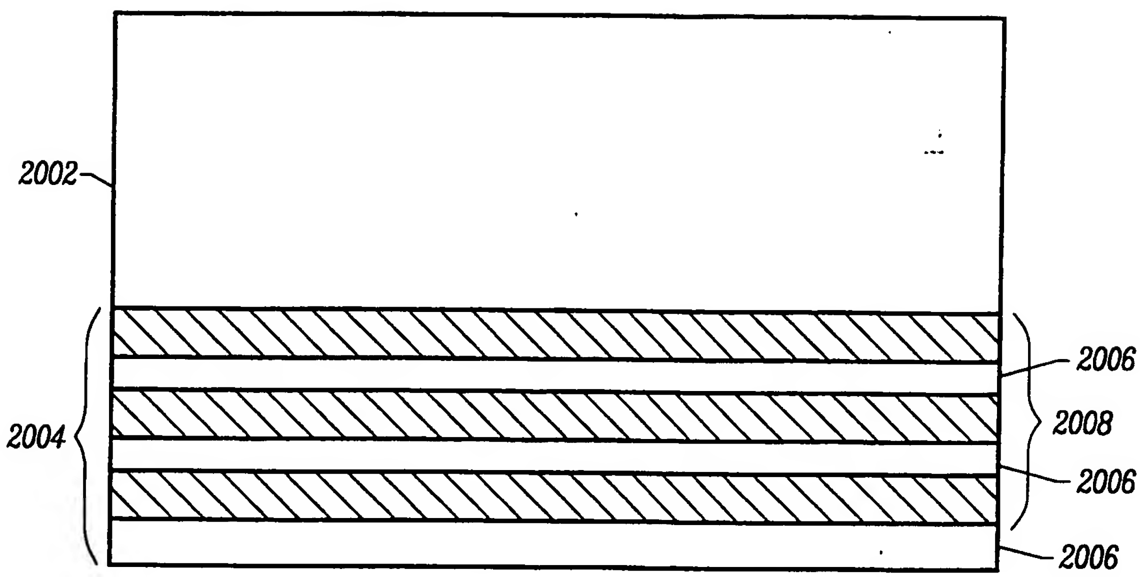


FIG. 20

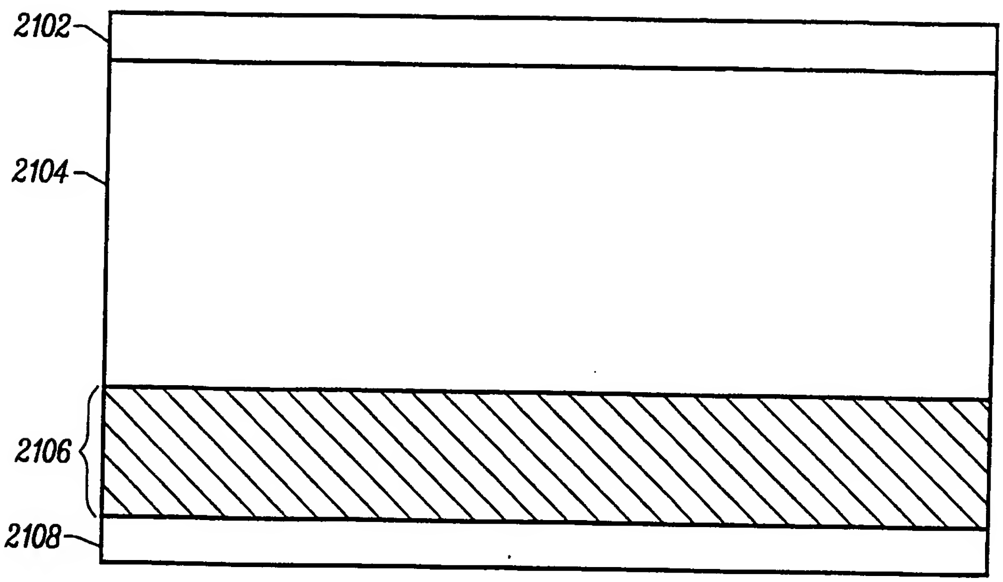


FIG. 21

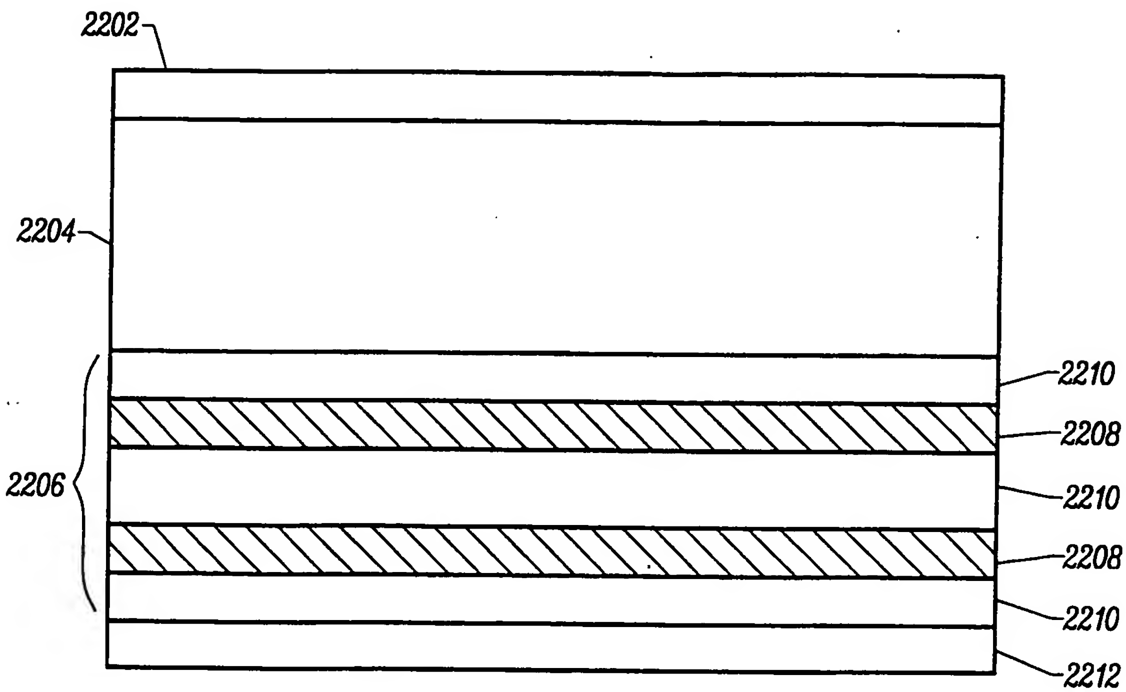


FIG. 22

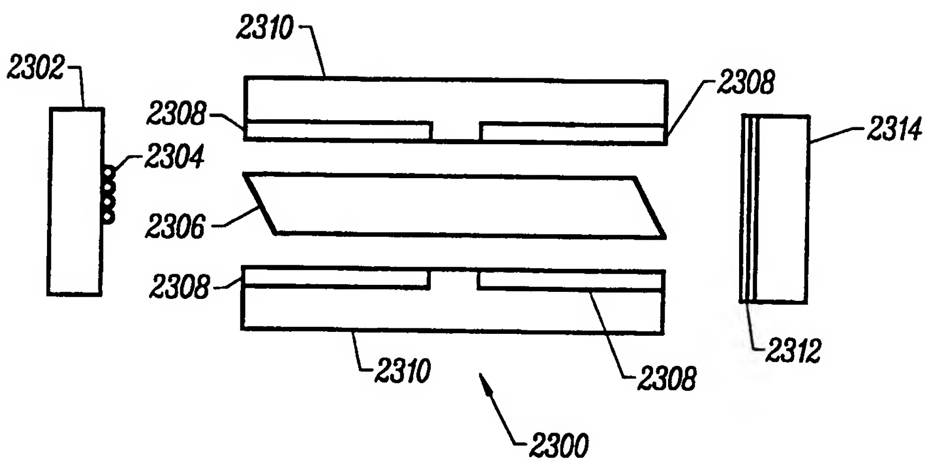

2310
2302
2308
2308
2304
2314
2306
2308
2312
2310
2308
2300

FIG. 23

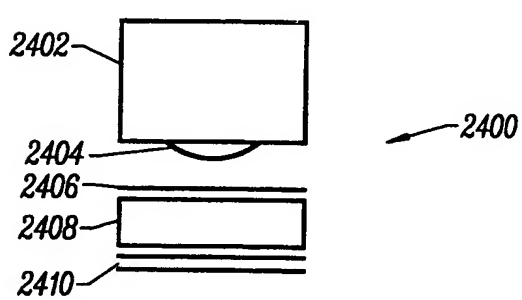

2402
2400
2404
2406
2408
2410

FIG. 24

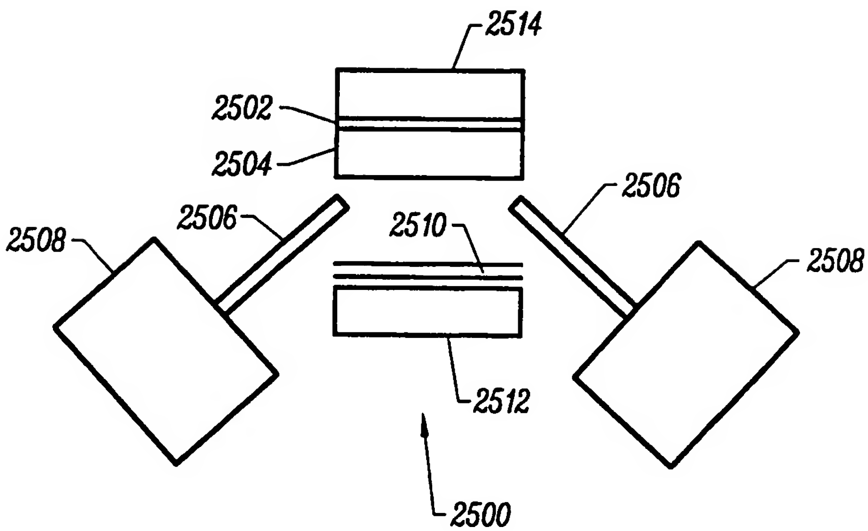


FIG. 25

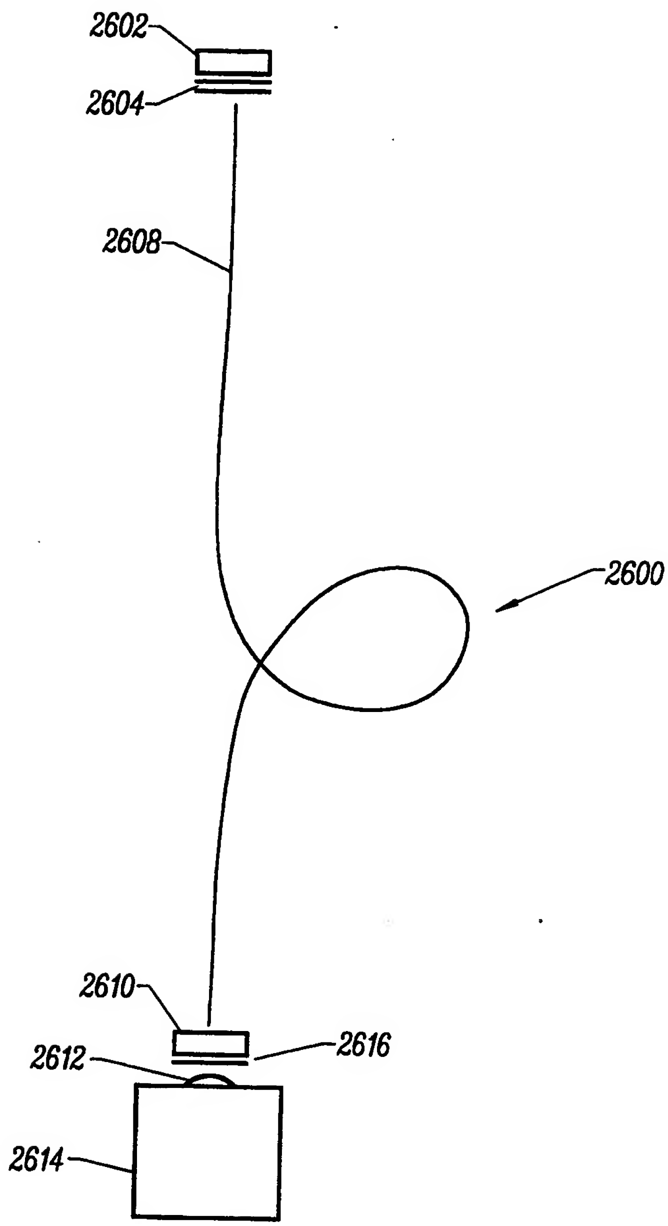


FIG. 26

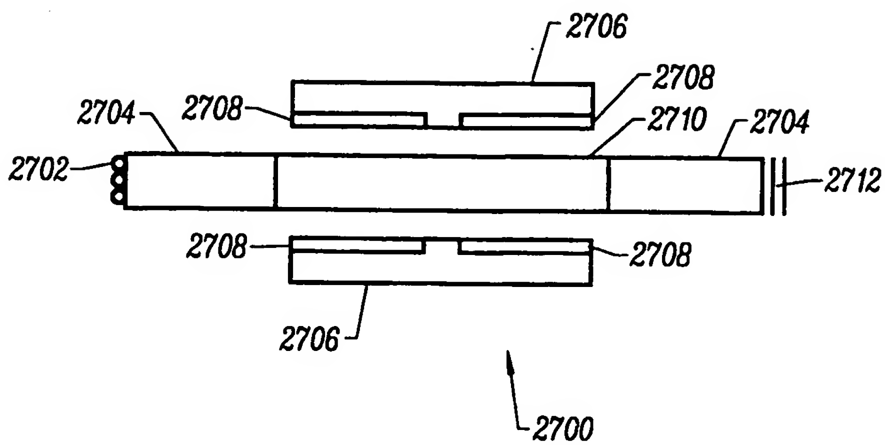

2706
2708
2704
2708
2710
2704
2702
2712
2708
2708
2706
2700

FIG. 27

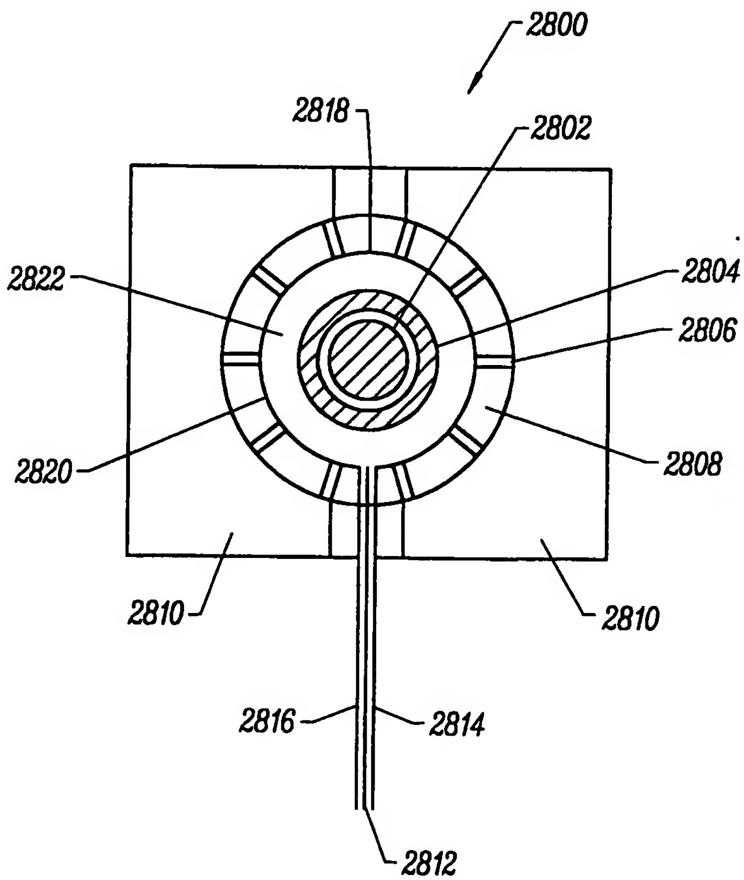

2800
2818
2802
2822
2804
2806
2820
2808
2810
2810
2816
2814
2812

FIG. 28

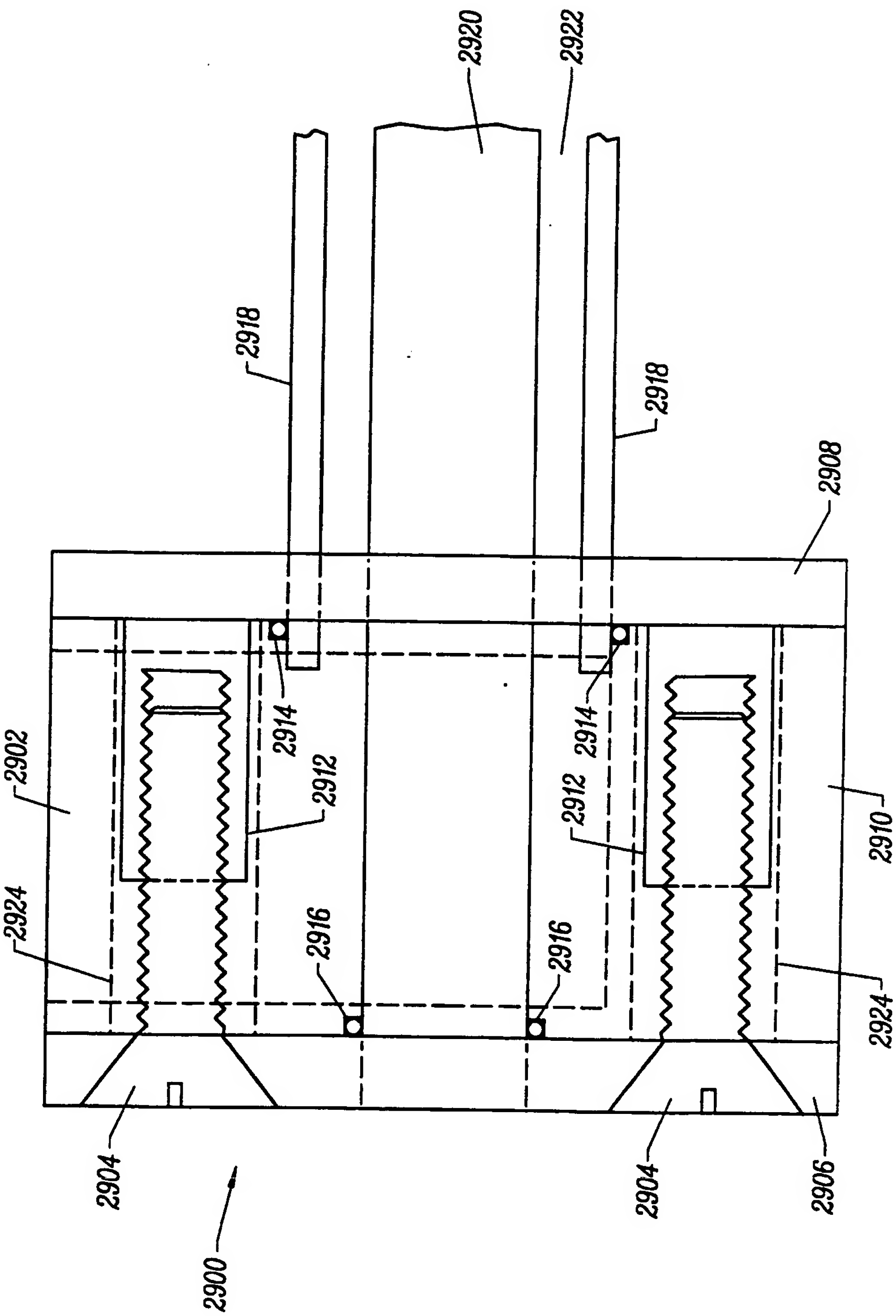

2920
2922
2918
2918
2908
2902
2914
2914
2912
2912
2910
2924
2916
2916
2924
2904
2904
2906
2900

FIG. 29

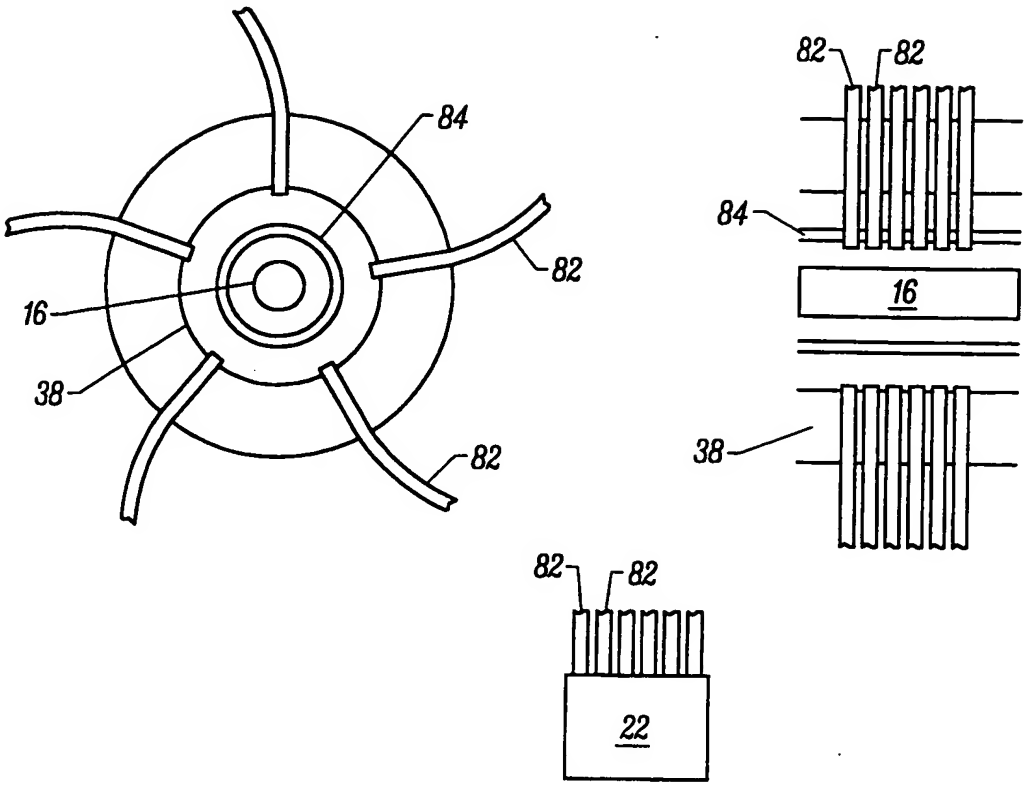


FIG. 30

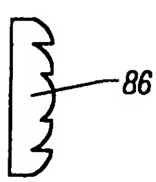


FIG. 31

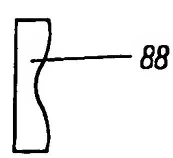


FIG. 32

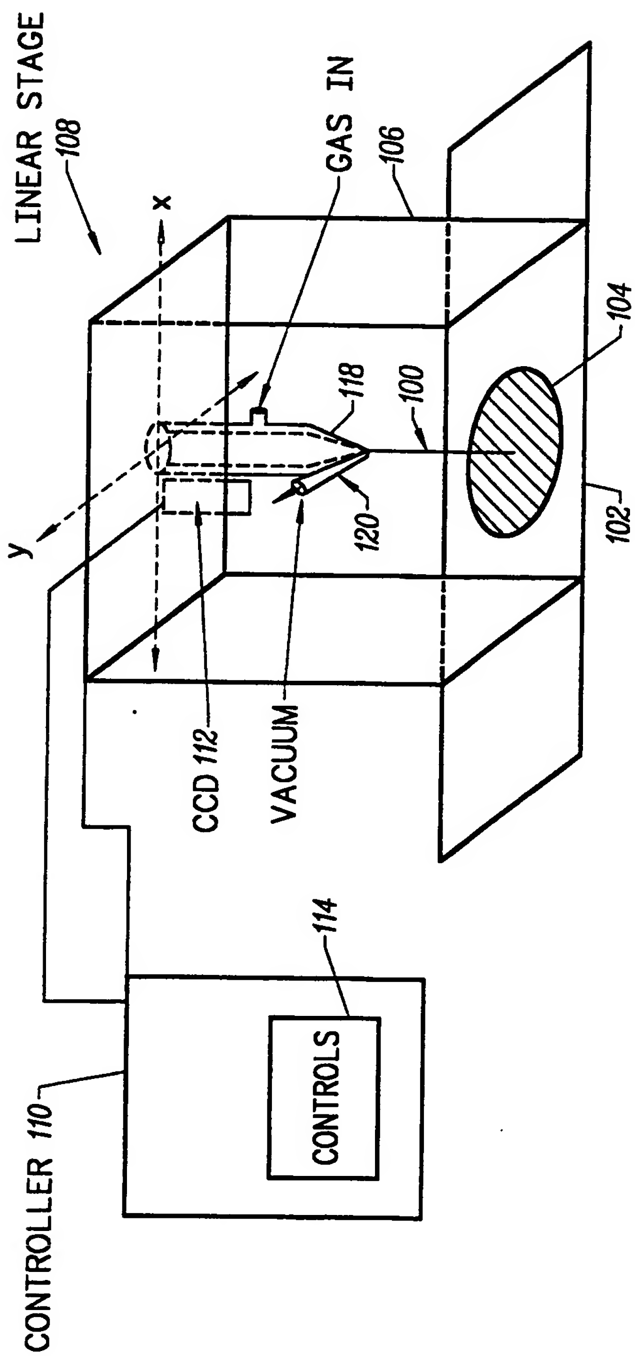

LINEAR STAGE
108
x
y
GAS IN
106
104
118
100
120
102
CCD 112
VACUUM
114
CONTROLS
CONTROLLER 110

FIG. 33

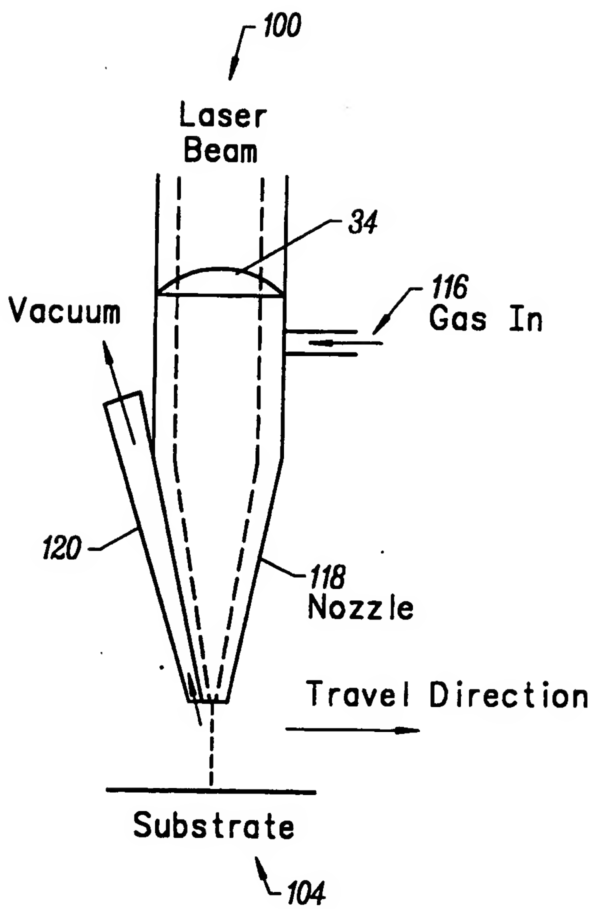

100
Laser
Beam
34
116
Gas In
Vacuum
120
118
Nozzle
Travel Direction
Substrate
104

FIG. 34

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/09594

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :HO1S 3/091
US CL :372/75
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 372/75 10,11,21,27,25,39,40,69,70,71,72,92,98,106,107

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

SEARCHED APS; search terms: laser? and substrate? and electro(w)optic? and pump? and polar? and gain?(2A)medium and high(w)voltage?(w)pulse?

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,123,026 A (FAN ET AL) 16 June 1992 (16/06/92), note entire document.	1-155
A	US 5,001,716 A (JOHNSON ET AL) 19 March1991 (19/03/91), note entire document.	1-155
A	US 5,034,951 A (EDELSTEIN ET AL) 23 July 1991 (23/07/91), note entire document.	1-155
A	US 5,291,505 A (NIELSEN) 01 March 1994 (01/03/94) , note entire document.	1-155

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 JUNE 1998	02 SEP 1998

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	BRIAN M. HEALY
Facsimile No. (703) 305-3230	Telephone No. (703) 308-2693